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THE USE OF SATELLITE-DERIVED SOUNDINGS IN THE AFGWC STRATOSPHERIC ANALYSIS MODELS,

BY

CAPT FRED P. LEWIS
MAJ TERRY C. TARBELL
CAPT JAMES E. HOKE

Technical note

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UNITED STATES AIR FORCE
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James A. Young

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The first successful use of satellite-derived soundings in the stratospheric analysis models of the Air Force Global Weather Central (AFGWC) occurred on 26 December 1979. A new procedure for the construction of the stratospheric first-guess fields was also instituted on that date. These new first-guess fields are based on satellite soundings. This Technical Note describes the changes that have been made to the stratospheric analysis procedure used at the AFGWC.

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PREFACE

On 26 December 1979, the first successful use of satellite-derived soundings in the stratospheric analyses occurred. Also, a new procedure for the construction of the stratospheric first-guess fields was instituted. These new first-guess fields are based on satellite soundings. This Technical Note (TN) describes these recent changes that have been made to the stratospheric analysis procedure used at the Air Force Global Weather Central (AFGWC).

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  Lt Col Richard C. Savage, AFGWC/TSIE
  Maj James L. Hatch, AFGWC/DOY

Captain Fred P. Lewis
Major Terry C. Tarbell
Captain James E. Hoke

1 August 1980

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1. INTRODUCTION

The stratospheric analysis models of the Air Force Global Weather Central (AFGWC) produce gridded analyses of wind, temperature, and height at the 70-, 50-, 30-, 20-, and 10-mb levels. These whole-mesh analyses are produced for the Northern Hemisphere, Southern Hemisphere, and Tropical grids (see Tarbell and Hoke (1979) for a review of the analysis models and Hayes and Hoke (1979) for an overview of the grid system).

The stratospheric analysis models use a method whose theory is described by Cressman (1959) and Moreno (1973). The details of the analysis technique as used at AFGWC have been given by Moreno (1973). In this method, observed data are used to modify a first-guess analysis field by a method of successive corrections. That is, the analysis is performed in several "scans". During a scan, which consists of one pass through the data, the first guess for that scan is altered. In the first scan data are used to update (correct) the first-guess field, which is provided by a previous analysis. The resulting field at the end of the first scan then becomes the first-guess field for the next scan, and so on. The final analysis is the field produced by the last scan.

Until recently, radiosonde observations (RAOBs) and rocketsonde observations (ROCOBs) were the only data available to the AFGWC stratospheric models. The advent of the current generation of satellite-borne sensors, however, has significantly changed this fact. In general, the quality of sounding observations derived from the observed satellite radiances is comparable to that of RAOBs. The satellite soundings potentially are available in far larger quantities than RAOBs. Also, satellite soundings are available in traditionally data-sparse areas.

In light of these facts, NMC began investigation of satellite soundings for use in their analysis models. During 1979, NMC began using satellite soundings operationally over the oceans of the Northern and Southern Hemispheres and globally in the stratosphere. Because of the high quality of satellite soundings, the experience gained at NMC on the use of these soundings, and the availability of soundings from Defense Meteorological Satellite Program (DMSP) satellites, we also incorporated satellite soundings into the AFGWC analysis models. On 26 December 1979, satellite soundings were successfully used in the AFGWC operational stratospheric analysis models along with conventional observations (RAOBs, ROCOBs, AIREPs, etc.). The purpose of this TN is to discuss how satellite-derived soundings have been used to improve the stratospheric analyses. The use of these soundings in the tropospheric analysis models is presented by Hoke, Tarbell, and Lewis (1980).

In Section 2 we review the stratospheric analysis technique used at AFGWC prior to 29 Dec 1979. Section 3 discusses the quality and availability of stratospheric satellite-derived soundings. The stratospheric analysis procedure used operationally at the National Meteorological Center (NMC) is presented in Section 4. In Section 5 the new AFGWC stratospheric analysis procedure is presented. Section 6 gives examples of the new stratospheric analyses. Finally, Section 7 contains the summary and conclusions.

2. THE PREVIOUS STRATOSPHERIC ANALYSIS PROCEDURE

Stratospheric analyses have been and continue to be made for the 00 and 12 GMT data times (T is either 00 or 12 GMT). Separate model runs are used for three different portions of the globe. The first stratospheric analysis for the Northern Hemisphere (MULTN2) begins at T+0450 (4 hours, 50 minutes after data time). An update analysis model (MULTN4) starts at T+0817. The Tropical stratospheric analysis model (TWAHI) begins at T+0636. Finally, the Southern Hemisphere stratospheric analysis model (SHMLT1) starts at T+0705. These times were specified by considering operational requirements, data availability, and computer availability.

2.1 Derivation of the First-guess Fields

For tropospheric analyses first-guess fields are often forecasts initiated from a previous data time. Because AFGWC does not use a forecast model for the stratosphere, the first-guess fields must be obtained in some other way.

The meteorological quality of first-guess fields is very important. If no observations are within the analysis-model scan radius for a given grid point, the final value analyzed at that grid point is the first-guess value at that grid point. Therefore, a good first guess is especially important in the stratosphere because relatively few RAOBs and ROCOBs are normally available, especially over oceans and remote land areas.

AFGWC receives approximately 1430 conventional upper-air soundings daily. Most of these observations are taken over land masses. Of these 1430, only about 950 soundings reach the 50-mb level and even fewer extend to the 10-mb level. McPherson (1980) stated the average number of RAOBs received daily at NMC is approximately 1356. Most of these observations are taken over Northern Hemispheric land masses.

Prior to 26 Dec 1979 the AFGWC stratospheric analysis models used a set of regression equations to derive the initial 70- through 10-mb temperature and height first-guess fields from the latest 100-mb analysis (Moreno, 1973). Lea (1961) and Povlowitz and Erickson (1965) computed these regression equations based on several years of stratospheric RAOB data. In general, regression equations are designed to fit a given set of values. In this case the regression equations were computed to fit several years of RAOB data (Finger et al., 1965). The use of regression equations permits the calculation of first-guess fields at higher levels (70 through 10 mb) in the atmosphere from a lower level (100 mb) without any additional observations at the higher levels. For example, a regression equation is used to calculate the thickness between the 100-mb and 50-mb levels for a given latitude band and season. This climatological thickness is added to the latest analyzed 100-mb height for that location to obtain the initial 50-mb height.

The complete first-guess fields are derived from a blend of persistence (the previous analyses) and the fields produced from the regression equations. Thus the complete first-guess fields are derived from the previous analysis at the given level, the current 100-mb level analysis, and climatology.

Eqs. (1) and (2) are the regression equations used for the 50-, 30-, and 10-mb heights and temperatures, respectively:

$$T_{k+1} = A_{o_{k,s}} + A_{1_{k,s}} H_k + A_{2_{k,s}} T_k \quad , \qquad (1)$$

$$H_{k+1} = B_{o_{k,s}} + B_{1_{k,s}} H_k + B_{2_{k,s}} T_k \quad , \qquad (2)$$

where

T_{k+1} = temperature (^oC) of the upper level,

T_k = temperature (^oC) of the lower level,

H_{k+1} = height (m) of the upper level,

H_k = height (m) of the lower level,

k = index of the level,

s = season (1 = spring, 2 = summer, 3 = fall, 4 = winter), and

A_x, B_x = the regression coefficients (x = 0, 1, or 2, where x is an index).

The values of the regression coefficients A and B as functions of latitude and layer (100 to 10 mb) are given in Appendix B. NMC uses these same regression equations and coefficients when an insufficient number of satellite soundings are available to provide the first-guess fields.

After the initial first-guess temperature and height fields are computed from (1) and (2), the 50-, 30-, and 10-mb fields are blended with persistence. Specifically, 60 percent of the persistence field is added to 40 percent of the initial first-guess (regression) analysis to form the final first-guess analysis (Moreno, 1973). The 70- and 20-mb first-guess fields are then computed from the 100-, 50-, 30-, and 10-mb first-guess fields, using (3) through (6):

$$H_{70mb} = 0.485\ H_{100mb} + 0.515\ H_{50mb} \qquad (3)$$

$$T_{70mb} = 0.5\ (T_{100mb} + T_{50mb}) \qquad (4)$$

$$H_{20mb} = 0.6362\ H_{30mb} + 0.3638\ H_{10mb} \qquad (5)$$

$$T_{20mb} = 0.5\ (T_{30mb} + T_{10mb}) \qquad (6)$$

Finger et al. (1965) reported that meteorologically appearing first-guess fields were produced using similar regression equations.

2.2 Analysis Problems

When an analysis model updates or corrects a first-guess field with an observation, data throw criteria are used. If the observation differs from the first-guess field by more than a specified amount (the data throw criterion), then the observation is disregarded.

Because it is desirable to use as many of the relatively few observations in the stratosphere as possible, the data throw criteria in the stratosphere were liberal (that is, less stringent) than in the troposphere. The liberal throw criteria in the stratosphere sometimes permit erroneous observations to be included in the final analysis. When a single observation is involved, it is possible for a nonmeteorological "bullseye" feature to result. The occurrence of these bullseye features in the Tropical analyses was detected by the United States Air Force Environmental Technical Applications Center (USAFETAC) in 1979. This problem led AFGWC to investigate the use of satellite soundings in the stratospheric analyses.

3. REMOTELY SENSED SOUNDINGS FROM DMSP AND NOAA SATELLITES

Currently the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DoD) under the Defense Meteorological Satellite Program (DMSP) have polar orbiting satellites with infrared and microwave sensors designed to measure meteorological characteristics of different levels of the atmosphere. The data from these sensors are used to provide remotely sensed atmospheric profiles of height and temperature.

3.1 Quality of DMSP and NOAA Satellite Soundings

With the advent of the latest generation of satellite-based radiation sensors, the quality of temperature and height soundings has improved greatly. AFGWC computes satellite soundings using radiances observed by the DMSP satellites. We also receive soundings that are computed by the National Environmental Satellite Service (NESS) and are based on radiances observed by NOAA satellites.

The DMSP satellites currently have two types of sensors measuring information for the purpose of deriving atmospheric soundings. These sensor types are Special Sensor H (SSH), an infrared sounder, and Special Sensor Microwave Temperature (SSMT), a microwave sounder. Atmospheric radiances measured with these instruments are converted to satellite-derived height and temperature soundings by software maintained by the Electromagnetic Systems Section (TSIE) at AFGWC.

Savage* (1980) compared DMSP SSMT soundings with RAOBs and NOAA TIROS-N Operational Vertical Sounder (TOVS) soundings. In Table 1 (taken from Savage*, 1980), we present an example of this comparison, contrasting RAOB versus RAOB, TOVS versus RAOB, TOVS versus SSMT, and SSMT versus RAOB coincident data. For this study coincident observations are defined as those taken within 3 hours and 100 nautical miles of each other. The TOVS and SSMT data compare favorably with one another and with RAOB data at all levels, including the stratosphere. In view of these statistics, Savage* (1980) suggested that the quality of the SSMT soundings is sufficient for operational use in the stratosphere.

Pryor et al. (1980) have demonstrated the usefulness of the DMSP SSH data in stratospheric analyses. They found that stratospheric temperature analyses based on SSH data were meteorologically reasonable. They investigated the sudden stratospheric warning events during January and February 1979 and found that DMSP SSH data were able to resolve these events accurately.

*Personal Communication, Richard C. Savage, Chief, Electromagnetic Systems Section, AFGWC.

TABLE 1. Differences between coincident soundings for different sounder types for the period Mar - Apr 1980

	RAOB - RAOB	TOVS - RAOB	TOVS - SSMT	SSMT - RAOB
20-mb height (m)	-43/97 (59)	-36/102 (125)	-35/82 (177)	-41/108 (173)
300-mb height (m)	- 8/45 (406)	1/57 (237)	3/61 (177)	-13/69 (334)
1000-mb height (m)	0/18 (399)	- 3/34 (244)	4/37 (153)	-12/28 (307)
1000 - 300-mb thickness (m)	- 9/45 (360)	4/45 (233)	- 0/43 (153)	- 3/57 (293)

NOTES:

1. Table entries have the following format: Mean difference/RMS difference (Sample size).

2. SSMT comparisons are world wide; all others are from data-rich Northern Hemispheric regions.

3. Two soundings are "coincident" if they are observed within 3 h of and are located within 100 nautical miles of each other.

4. A 1 C change at 20 mb corresponds to a 20-mb level height change of 115 m. A 1 C change in the 1000-300 mb thickness corresponds to a thickness change of 35 m.

Data from the NOAA satellites are converted into satellite soundings by NESS (Smith et al., 1979). The TOVS instrumentation is currently carried on the TIROS-N and NOAA-6 satellites. The TOVS package contains three sensors that observe both infrared and microwave radiation from lower, middle, and upper atmospheric levels.

Phillips et al. (1979) pointed out that TOVS soundings are useful and provide valuable meteorological information. They found differences between the TOVS soundings and RAOBs were usually less than 2 C (1.5 C in the Tropics). They recommended the soundings be used operationally at NMC. Phillips and Desmarais (1979) stated that the satellite temperature profiles have appreciably less variance than RAOBs. Also, they pointed out that satellite soundings for oceanic areas are derived primarily from satellite soundings colocated with RAOBs over land areas. In the future, increased emphasis will be placed on maritime colocations.

Gelman and McInturff (1979) found that meteorologically appearing stratospheric analyses were produced when TOVS data were incorporated. They suggested using satellite-derived soundings at or below 50 mb over oceans and above 50 mb over the entire globe.

In summary, an increasingly large body of evidence supports the statement that atmospheric soundings derived from the current generation of satellite-borne instruments are of a quality comparable to RAOBs. We therefore hypothesized that soundings from both DMSP and NOAA satellites should be used operationally in the AFGWC stratospheric analysis models.

3.2 Availability of DMSP and NOAA Soundings

Unfortunately, the availability of satellite soundings can be highly variable. There are no operational SSH sounders at the present time. A SSMT sounder is providing radiance data from DMSP satellite F-4. About 600 SSMT soundings are available from this source daily. DMSP satellite F-6 with its SSMT sensor is scheduled for launch during the summer of 1981.

Phillips et al. (1979) stated that NESS computes about 8000 TOVS soundings per day. Of that number, about 2000 are distributed daily over the Global Telecommunications System (GTS). Some of these do not arrive at AFGWC in time to be included in the stratospheric analyses. Also, communications and/or computer problems sometimes further decrease the number of TOVS soundings available.

The use of satellite soundings in the stratosphere increases the amount of data available to the analysis models from approximately 1400 observations per day to 2700 per day with the additional satellite data going into data-sparse ocean areas. Thus, using satellite soundings will be important, because the quality of any objective analysis is almost directly related to the amount of data used when the data density is low. With even more high-quality satellite soundings expected in the future, results from using these data sources appear very promising.

4. THE STRATOSPHERIC ANALYSIS PROCEDURE AT NMC

NMC began using TOVS soundings in the operational stratospheric analyses in October 1979 (Phillips et al., 1979). Satellite-derived temperatures and heights are used to compute first-guess fields and in the final analysis (M. Gelman, personal communication). For the 00 and 12 GMT analyses, satellite soundings observed within 3 h of analysis time are used in the final analysis. When compared to available conventional observations this dramatically increased the number of stratospheric observations used in the NMC analyses.

Prior to October 1979, NMC used a combination of regression equations and persistence to derive the stratospheric first-guess fields (Finger et al., 1965). Beginning in October 1979, NMC replaced the use of regression equations for the first-guess fields with an analysis of satellite data for a 12-h period, from 9 h prior to data time to 3 h after data time. A 12-h period is used because global coverage can be obtained from each satellite. Also, the use of a 12-h period in the stratosphere can be justified because, as pointed out by Finger et al. (1965), the stratosphere normally varies with time much more slowly than the troposphere.

The final first guess is calculated from 50 percent of the analysis using 12 h of satellite data and 50 percent of persistence. Combinations other than 50:50 were tried but were not as good (M. Gelman, personal communication). To date, NMC has had good results using TOVS data in their stratospheric analyses.

5. THE NEW AFGWC STRATOSPHERIC ANALYSES TECHNIQUE.

AFGWC first successfully used DMSP and NOAA satellite soundings in their stratospheric analysis models on 26 December 1979. These data are used for the following reasons:

a. Nonmeteorological bullseye features have occasionally occurred in the AFGWC stratospheric analyses in the Tropics (see Section 2.3).

b. The accuracy of the DMSP and TOVS soundings in the stratosphere is comparable to RAOBs (see Section 3.1).

c. The satellite soundings are available in sufficient numbers so that the number of observations available to the stratospheric analysis models would more than double (see Section 3.2).

d. NMC incorporated TOVS soundings operationally into their stratospheric analyses in October 1979. NMC scientists have been pleased with the results (see Section 4).

e. Finally, satellite soundings are internally consistent. Observed radiances are made over the sensor's field of view. These radiances are then converted into satellite soundings using statistical techniques. Adjacent satellite soundings from a particular spacecraft are almost always consistent with one another. On the other hand, adjacent stratospheric RAOBs are not always consistent with each other. There are numerous possible reasons why this can and does occur. One reason is that the radiosondes are made by different manufacturers.

5.1 The Stratospheric Analysis Procedure

We adopted the same general analysis procedure as used by NMC. That is, for stratospheric analyses at the 00 and 12 GMT data times, satellite soundings observed within three hours of data time are used. However, at AFGWC DMSP soundings are used in addition to TOVS soundings.

The procedure for deriving the first-guess height and temperature fields is also patterned after the NMC procedure. DMSP and NOAA satellite soundings from 9 h before to 3 h after data time are analyzed using the Cressman analysis procedure to provide the satellite portion of the first guess. (The first guess for the satellite portion is persistence from the prior analysis.) The satellite portion is blended 50:50 with persistence to obtain the final first-guess fields. Note that if less than 100 satellite soundings are available for the 12-h first-guess period in the hemisphere being analyzed, this first-guess procedure is not used. Instead, we revert to the regression equation procedure presented in Section 2.2.

We adopted one change that involved data throw criteria which was not patterned after the work of NMC. Essentially, the use of satellite-derived soundings allows the data throw criteria for the Tropical stratospheric analyses model to be more stringent. Table 2 summarizes the changes in the throw criteria for the height and temperature analyses. The throw criteria for the wind analysis were not changed.

Table 2. Data Throw Criteria Used by the Tropical Stratospheric Analysis Model

	THROW CRITERIA		
	1965	1970s prior to 26 Dec 1979	Since 26 Dec 1979
Temperature			
Scan 1	12 C	15 C	12 C
Scan 2	9 C	12 C	10 C
Scan 3	7 C	10 C	9 C
Scan 4	5 C	8 C	7 C
Height			
Scan 1	Unknown	600 m	200 m
Scan 2	"	400 m	150 m
Scan 3	"	200 m	125 m
Scan 4	"	100 m	100 m

5.2 Derivation of TOVS Heights and Temperatures

Additional computations are applied to the TOVS, SSH, and SSMT data before using them in the stratospheric analyses. First, the NESS data received over the GTS are thicknesses only. Thus, temperature and height values must be computed from these thickness values. To compute the 70- to 10-mb heights the TOVS thicknesses are simply added to the most current 100-mb height analysis interpolated to the observation points.

The TOVS temperatures are computed directly from the thickness values using (7) and (8) (see Fig. 1):

$$T_k = g \Delta Z_k / (R \ln (P_{k-1}/P_k)) \qquad (7)$$

$$T_k = \begin{cases} \dfrac{\bar{T}_{k+1} \ln (P_{k-1}/P_k) + \bar{T}_k \ln (P_k/P_{k+1})}{\ln (P_{k-1}/P_{k+1})}, & k=1,5 \\ \bar{T}_k & \text{for } k = 6 \text{ (10 mb)} \end{cases} \qquad (8)$$

where

k = level index (1 through 6),

$P_{k = 1, 2, .., 6}$ = 100, 70, 50, 30, 20, 10 mb,

T_k = temperature (C) at level k,

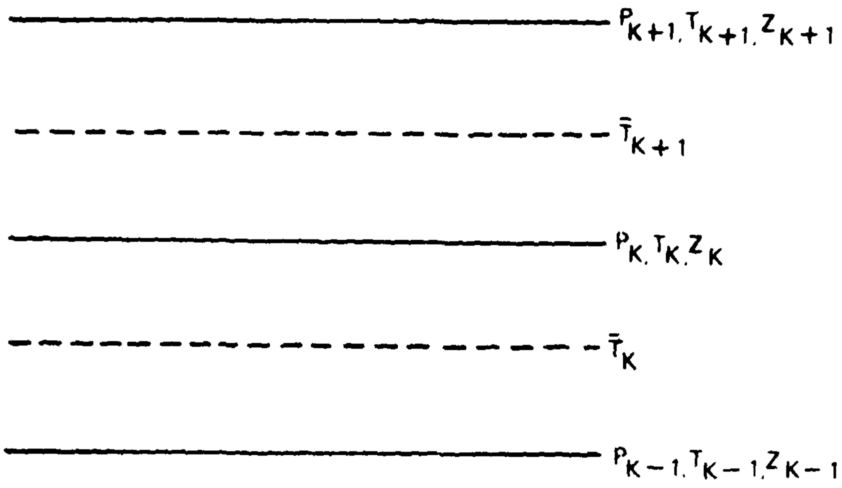


Fig. 1. Vertical depiction of the levels used in the computation of TOVS temperatures.

$\overline{T}_k$ = hydrostatically computed mean temperature (C) between level k and k-1,

Z_k = the thickness (m) for level k to k-1,

g = acceleration of gravity, and

R = universal gas constant (287 $m^2s^{-2}deg^{-1}$).

Eq. (8) represents the temperature at level k computed from a logarithmic interpolation in pressure.

The SSH and SSMT height soundings are stored in the AFGWC data base following their calculation from observed radiances. Because a new 100-mb analysis is stored in the data base after the SSH and SSMT height profiles have been calculated and stored, we add the SSH and SSMT thicknesses above 100-mb to this latest 100-mb analysis to compute the 70- through 10-mb height values.

5.3 The Correction of Daytime Stratospheric Temperatures from RAOBs

At stratospheric levels during daylight hours, a radiosonde temperature sensor may respond to direct solar radiation as well as the actual stratospheric temperature. The direct solar radiation causes the radiosonde to report a warmer air temperature than actually exists. The size of the temperature difference due to solar radiation varies with instrument type, latitude, time of day, time of year, and instrument altitude. McInturff et al. (1979) have presented a more comprehensive discussion of this topic. At and above 100 mb these temperature differences are on the order of 1 C. In some cases, however, the solar radiation correction can be greater than 10 C at 10 mb. The height field is also corrected. A typical height correction is about 20 m. McInturff et al. (1979) presented the latest available solar radiation corrections (differences) for both temperature and heights. These corrections are now being used in the AFGWC stratospheric analysis models.

5.4 Satellite Soundings and the AFGWC Stratospheric Analyses.

We have discussed the new AFGWC stratospheric analysis procedure and its use of satellite soundings. We have monitored the satellite soundings used operationally in the stratospheric analyses and found their quality to be good. No instances have been detected that would infer satellite soundings should not be used. In the next section we will present some examples of the new stratospheric analysis procedure.

6. EXAMPLE AFGWC STRATOSPHERIC ANALYSES

The new stratospheric analysis procedure has improved the analyses over the entire globe. In this section we present three cases of these improved analyses.

In the first case, we compare the Tropical 10-mb height analyses with and without satellite-derived soundings for 00 GMT 27 Dec 1979. This example suggests that the bullseye problem has been eliminated from the Tropical analyses. The second case is a series of Northern Hemispheric analyses for the 10-mb level from 10 Feb 1980 to 12 Mar 1980. During this period a sudden stratospheric warming occurred. The term sudden stratospheric warming refers to the irregular wintertime stratospheric warmings of approximately 50°C that occurs over a period of 1 to 3 weeks. The third case presents comparisons of the AFGWC and NMC 50-mb analyses for 1 Jan 1980 and 7 Jan 1980. These analyses are typical of all the AFGWC and NMC 10- and 50-mb analyses that were compared for the period from 28 Dec 1979 to 8 Jan 1980.

6.1 Tropical 10-mb Height Analysis, 00 GMT 27 Dec 1979

Bullseye features have been a problem in the Tropical stratospheric analyses. A typical example of one of these features is given in Fig. 2. This figure shows the 27 Dec 1979 00 GMT 10-mb height analysis for the Tropical portion of the Pacific Ocean with the previous analysis technique. A bullseye feature is evident in the central Pacific. This feature is the result of a single RAOB that was in a data-sparse region and that was significantly different from the first-guess analysis. The Cressman analysis technique spread this single RAOB into the all too familiar circular pattern (the bullseye) in Fig. 2.

Fig. 3 shows the 10-mb height analysis valid at the same time but produced by the new analysis technique. This technique utilizes DMSP and TOVS satellite soundings in data-sparse oceanic areas to compute the first-guess and final analyses. The two analyses show the same general characteristics except for the bullseye which, as expected, was eliminated in the analysis that included satellite soundings. The new analysis also appears to have more reasonable gradients in the height field. That is, stronger gradients occur near 40°N and 40°S.

We have monitored the Tropical stratospheric analyses since satellite soundings have been incorporated operationally and no bulleyes have occurred. In our opinion, the quality and reliability of the stratospheric analyses in the Tropics have improved significantly.

6.2 Sudden Stratospheric Warming (Feb-Mar 1980)

Among the most intriguing atmospheric phenomena are the sudden warmings that occur irregularly in the Northern Hemispheric stratosphere (Lordi, 1978; Schoeberl, 1978). During the Northern Hemispheric winter the stratospheric pattern typically consists of a cold polar region (at 10 mb the temperature is about -70°C) with a strong temperature gradient from 45°N to the North Pole (Holton, 1972). From thermal wind considerations this leads to a

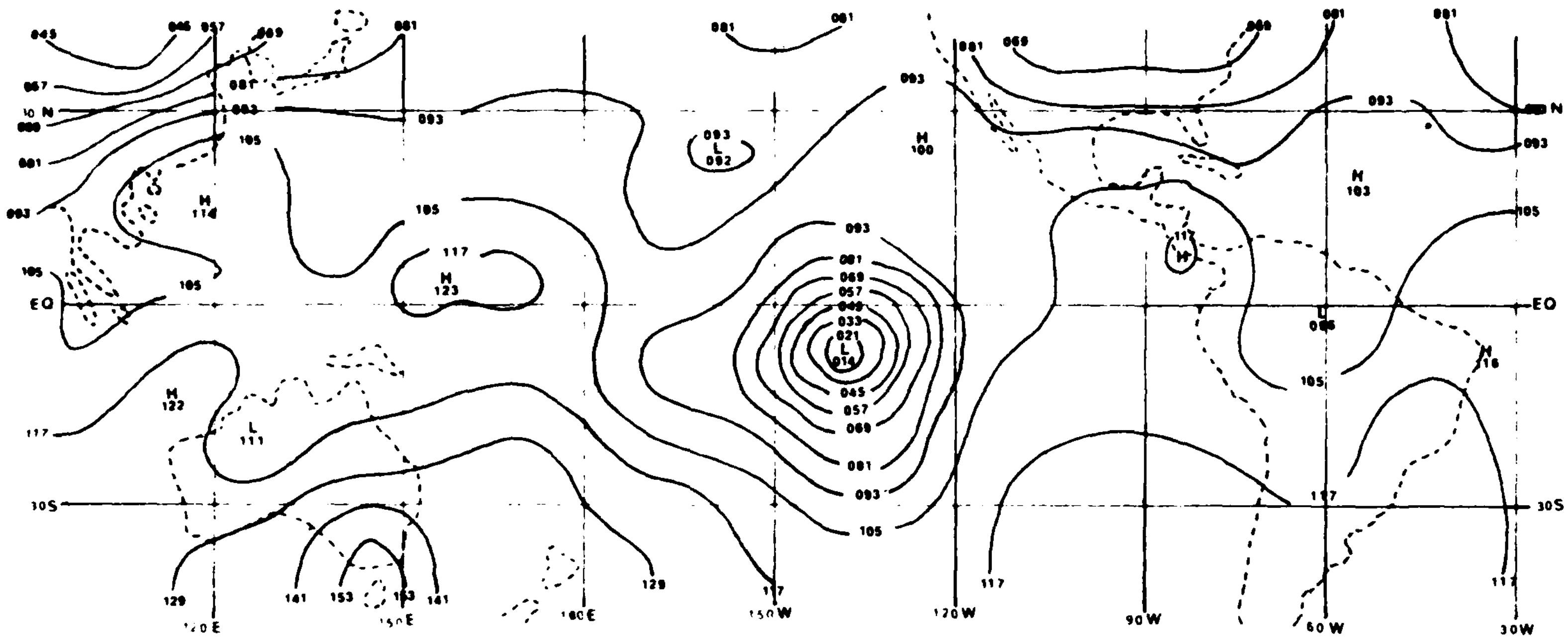


Fig. 2. AFGWC Tropical 10-mb height analysis for 00 GMT 27 Dec 1979 computed by the previous analysis technique (see text). The contour interval is 120 m.

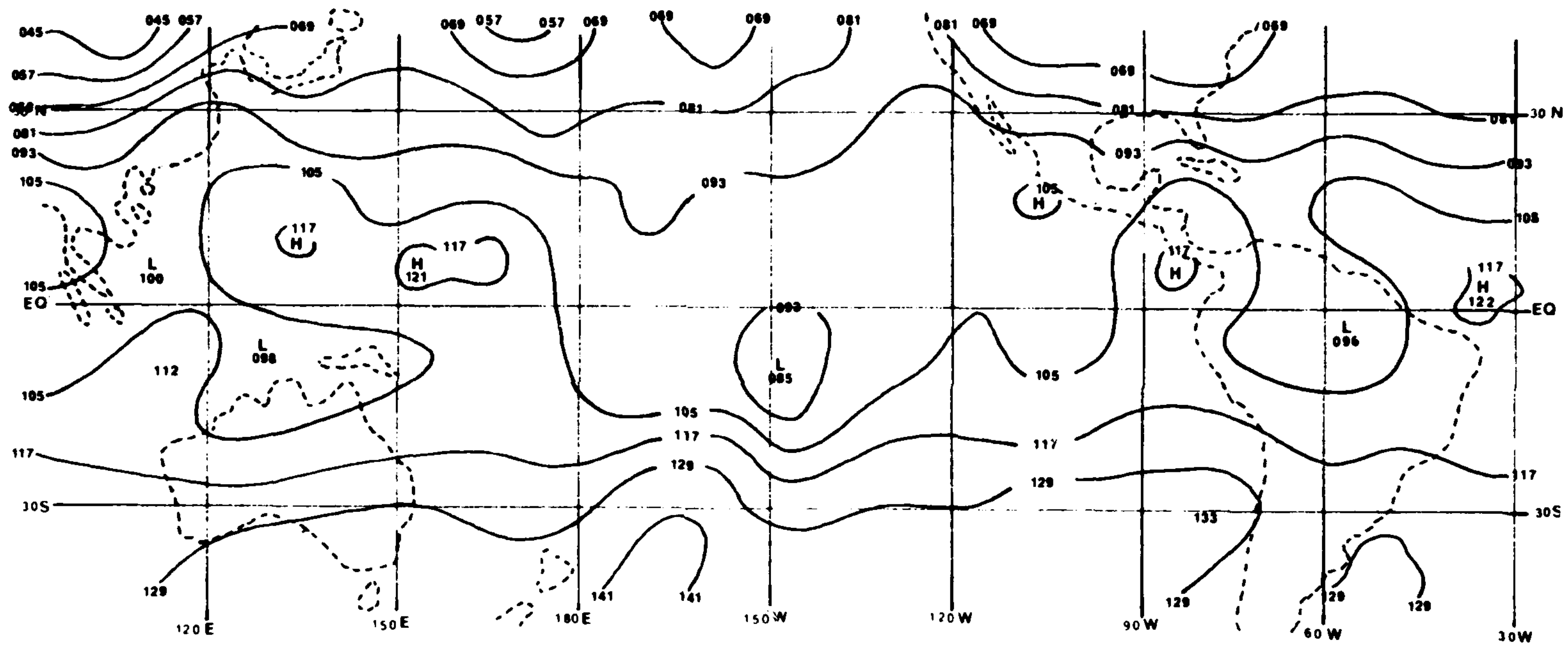


Fig. 3. AFGWC Tropical 10-mb height analysis for 00 GMT 27 Dec 1979 computed by the new analysis technique (see text). The contour interval is 120 m.

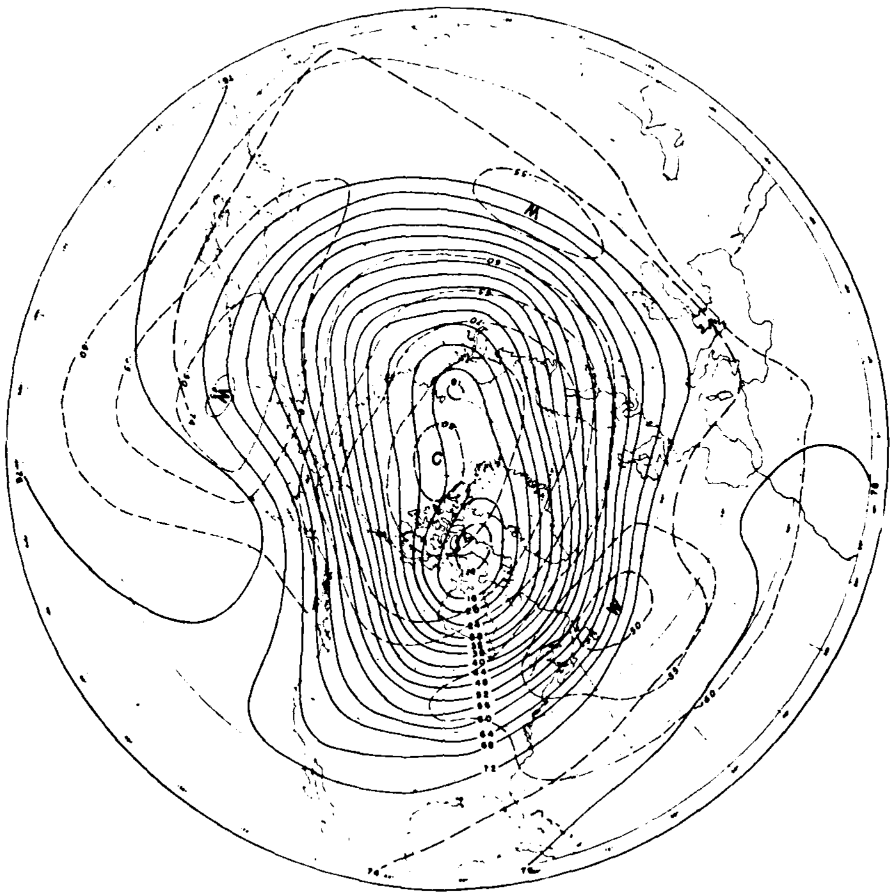
strong, almost circumpolar, westerly jet (the polar night jet). The corresponding height field consists of a polar low dominated by a wavenumber 1 component with a weaker wavenumber 2 component.

During mid and late winter, this usual pattern can, in less than two weeks, change to one where the stratospheric polar regions are about 50°C warmer (Holton, 1975). The temperature gradient north of 45°N reverses and the polar night jet is replaced by easterly flow. The corresponding height field changes from a low to a high near the North Pole.

The basic mechanism of a sudden warming as envisioned by Matsuno (1971) consists initially of an anomalous amplitude increase of the tropospheric stationary planetary waves in wavenumbers 1 and 2. This leads to enhanced wave propagation into the stratosphere. During the winter the only waves that can propagate energy vertically from the troposphere to the stratosphere are essentially wavenumbers 1 and 2. This phenomenon was explained by Charney and Drazin (1961). Given a strong westerly flow in the winter stratosphere, they showed that all vertically propagating stationary quasi-geostrophic waves will be damped exponentially with the exception of the longest waves. The ultra-long waves (ULWs) of the troposphere are nearly stationary and quasi-geostrophic. This upward ULW propagation leads to increased poleward transport of heat by eddy heat fluxes (Eliassen and Palm, 1961). This helps cause the reversal of the northward temperature gradient for a given layer in a matter of a few days. This reversal in the temperature gradient decelerates the mean zonal westerly flow in that layer to the point of producing an easterly current, forming a critical level. The stationary-wave critical level occurs at the point where the mean zonal wind is zero. The critical level blocks further vertical propagation of planetary-scale waves (Charney and Drazin, 1961). This causes a concentration of the zonal wind deceleration near the critical level, and hence a downward propagation of the critical level. The polar night jet is then replaced at lower and lower levels by an easterly flow and sudden stratospheric warming is underway.

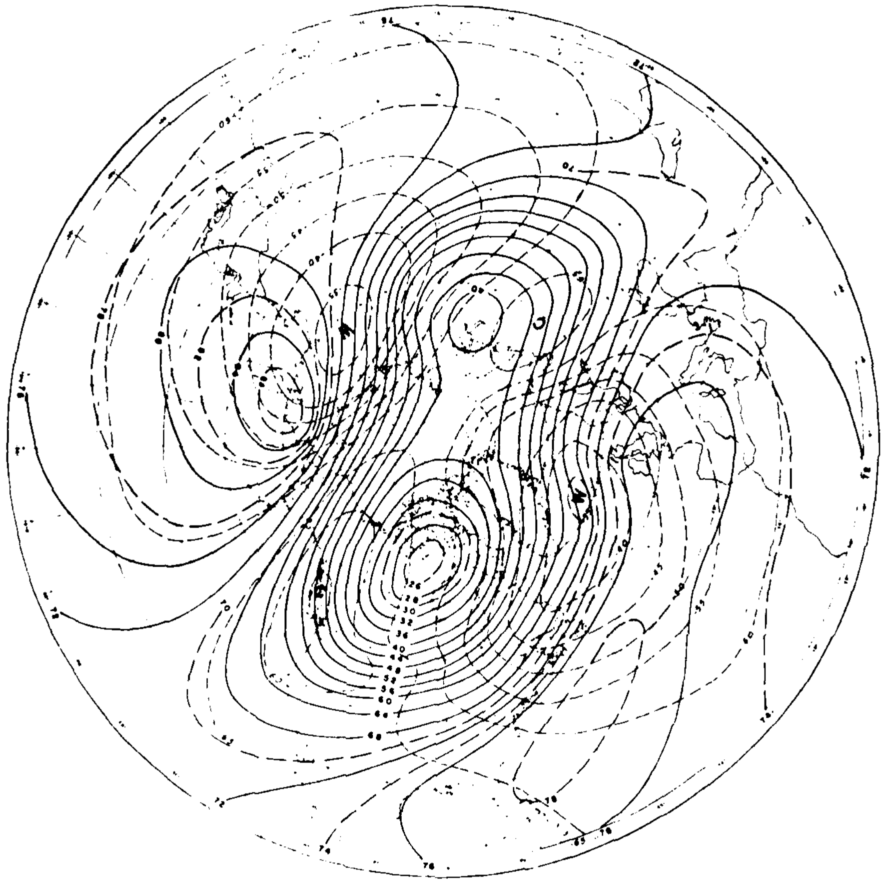
An example after Reed et al. (1963) of a sudden stratospheric warming during January and February 1957 at the 50-mb level is given in Figs. 4a, 4b, and 4c. These three charts represent a typical chain of events that occur during a wavenumber 2 sudden stratospheric warming. Note that the height analysis in Fig. 4a on 25 Jan 1957 was dominated by circumpolar flow composed almost entirely of wavenumber 1. The coldest temperatures (less than -80°C) occurred very near the North Pole. By 4 Feb 1957 (Fig. 4b) the circumpolar flow had started to break down and form two centers, one over North America and the other over northern Asia. Two distinct warm pockets had formed over the North Atlantic and North Pacific. On 9 Feb 1957 (Fig. 4c) there were two distinct closed lows and highs. The circumpolar vortex had completely broken down leaving the warmest temperatures very near the North Pole. The height field was now clearly dominated by a wavenumber 2 pattern.

During the months of February and March 1980 a sudden stratospheric warming at the 10-mb level was analyzed by the new analysis technique. Figs. 5 through 16 show Northern Hemispheric analyses from 10 Feb 1980 to 12 Mar 1980.



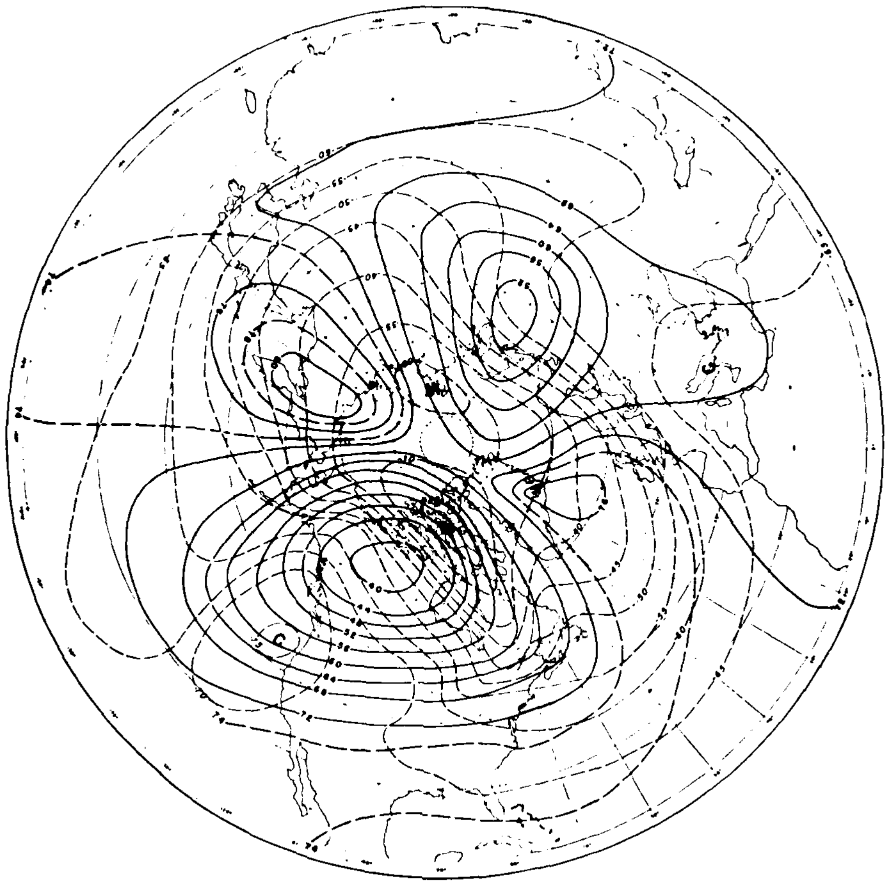
a. 25 Jan 1957

Fig. 4. The 50-mb height field (solid contours, interval 100 ft) and temperature field (dashed contours, interval $5^{\circ}C$) for a sudden stratospheric warming during January and February 1957. Analyses taken from Reed et al., (1963).



b. 4 Feb 1957

Fig. 4. (Continued).



c. 9 Feb 1957

Fig. 4. (Continued).

Figs. 5 and 6 are the 12 GMT 10 Feb 1980 analyses of 10-mb height and temperature, respectively. The height field at this time was dominated by a wavenumber 1 and 2 pattern with a cold circumpolar low. The temperature was coldest (about - 77°C) near the North Pole.

Figs. 7 and 8 are the 10-mb height and temperature analyses, respectively, for 12 GMT 18 Feb 1980. The height field was still strongly dominated by wavenumbers 1 and 2. The circumpolar feature of Fig. 5 had moved southward from the pole with the high over the North Pacific strengthening. The temperature field (Fig. 8) showed a much larger area warmer than -40°C over the North Pacific than shown in Fig. 6. The maximum temperature in this region had warmed from -33°C to -27°C. The coldest region had moved southward from the North Pole into northern USSR.

At 12 GMT 28 Feb 80, the 10-mb height field (Fig. 9) was mainly dominated by wavenumber 1. The low over northern USSR had started to weaken and the high over the North Pacific had moved into the Aleutians and strengthened. The 10-mb temperature field (Fig. 10) showed a strong pocket of warmer air (maximum -14°C) over northern Asia and near the North Pole. The coldest temperatures were now located between England and southern Greenland. The warm pocket near the North Pole constituted a warming of almost 50°C from its value at 12 GMT 10 Feb 1980 (Fig. 6). Thus, by this time the sudden stratospheric warming was progressing strongly.

The 10-mb height analysis for 12 GMT 2 Mar 1980 (Fig. 11) was again dominated by wavenumber 1 but a stronger wavenumber 2 component at lower latitudes was more evident than in the previous analysis. The highest heights were now located over North America and the lowest heights over northern Europe. The circumpolar low was clearly being replaced by an area of high pressure. In the 10-mb temperature analysis for 12 GMT 2 Mar 1980 (Fig. 12), a warm pocket (-16°C) now encompassed the North Polar region. The temperature gradient from 45°N to the North Pole had completely reversed from the initial values on 10 Feb 80 (Fig. 6).

By 12 GMT 4 Mar 1980, the 10-mb height field (Fig. 13) showed a high over North America. The low over northern Europe in Fig. 11 had now split into two distinct centers, one over Europe and the other centered near Florida. This pattern bears some resemblance to Fig. 4c, the 1957 stratospheric warming case presented by Reed et al. (1963). The 10-mb temperature analysis for 12 GMT 4 Mar 1980 (Fig. 14) no longer showed the warmest temperatures near the North Pole. This seems reasonable because the high in Fig. 13 was located to the south of the polar region.

Figs. 15 and 16 give the 10-mb height and temperature analyses for 12 GMT 12 Mar 1980. The split in the 12 GMT 12 Mar 1980 height field (Fig. 15) had disappeared and was replaced by a pattern dominated by wavenumber 1. Both the low and high features had weakened. This pattern resembles the 10-mb height analysis on 28 Feb 1980 (Fig. 9). The 10-mb temperature analysis showed a warm pocket (maximum -26°C) located at about 75°N and 90°W. This 10-mb temperature pattern also resembles the temperature pattern of 28 Feb 1980.

The height field throughout the period presented here appeared to oscillate between a pattern dominated by wavenumbers 1 and 2 and a pattern

dominated by wavenumber 1. The temperature field also appeared to oscillate from the polar regions being warmer (about -15°C) to the polar regions being cooler (about -35°C). These oscillations may be due to nonlinear interactions of wavenumber 0, 1, and 2, as suggested by Lordi (1978) in a numerical simulation of a sudden stratospheric warming.

We believe that the analyses of the Feb-Mar 1980 sudden stratospheric warming case presented here have demonstrated the usefulness of the DMSP and TOVS satellite soundings. These soundings enabled the detection and following of the sudden stratospheric warming even though its origin appeared to be in the data-sparse Northern Pacific. In the past and before satellite data were included in the analyses, synthetic data (bogus) often had to be added to analyze properly for sudden stratospheric warming.

6.3 Comparison of NMC and AFGWC Stratopsheric Analyses

To test the quality and accuracy of the new stratospheric analysis procedure we compared the stratospheric analyses of AFGWC and NMC. The NMC analyses are the only other operational objective stratospheric analyses produced in the United States. The 50- and 10-mb AFGWC height and temperature analyses for the period from 28 Dec 1979 to 10 Jan 1980 compared very favorably with the NMC analyses. We present two representative examples of this comparison for the Northern Hemisphere.

The NMC 50-mb height and temperature analyses for 12 GMT 1 Jan 1980 (Fig. 17) were very similar to the corresponding AFGWC height (Fig. 18) and temperature (Fig. 19) analyses. The position of the circumpolar vortex in both height and temperature analyses is essentially the same. The analyzed height value for the center of the circumpolar vortex differed by 140 m. The Aleutian high on both charts was located in nearly the same position and had the same central height value. The positions of the ridges and troughs in both height analyses were identical. The temperature fields showed warm and cold centers in the same regions of the Northern Hemisphere. The coldest temperatures in the polar regions of both analyses were less than -80°C. The warmest temperatures in both analyses were located in the North Pacific with values greater than -50°C.

The NMC 50-mb height and temperature analyses for 12 GMT 7 Jan 1980 (Fig. 20) differed little from the corresponding AFGWC height (Fig. 21) and temperature (Fig. 22) analyses. The only significant difference between the two height analyses was in the Central Pacific. The low height center in the NMC analysis was not present in the AFGWC height analysis. The temperature analyses showed very little difference.

We have concluded based on these and other cases that the AFGWC and NMC stratospheric analyses are comparable. Of course, there were some minor differences between the two analyses. However, the overall features in both the temperature and height fields were very similar. This good agreement was not surprising because both AFGWC and NMC used satellite soundings in the stratospheric analyses. The quantity and sources of satellite soundings are, however, different.

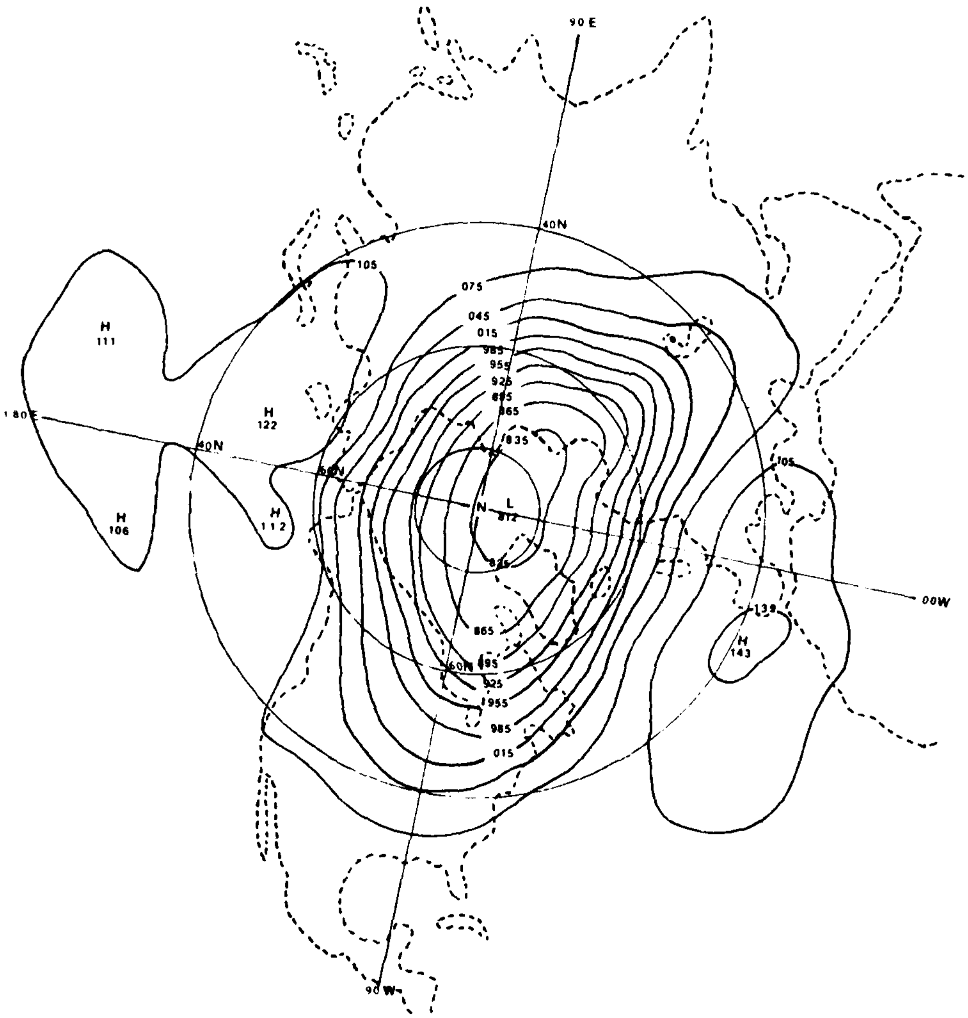


Fig. 5. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 10 Feb 1980. The contour interval is 300 m.

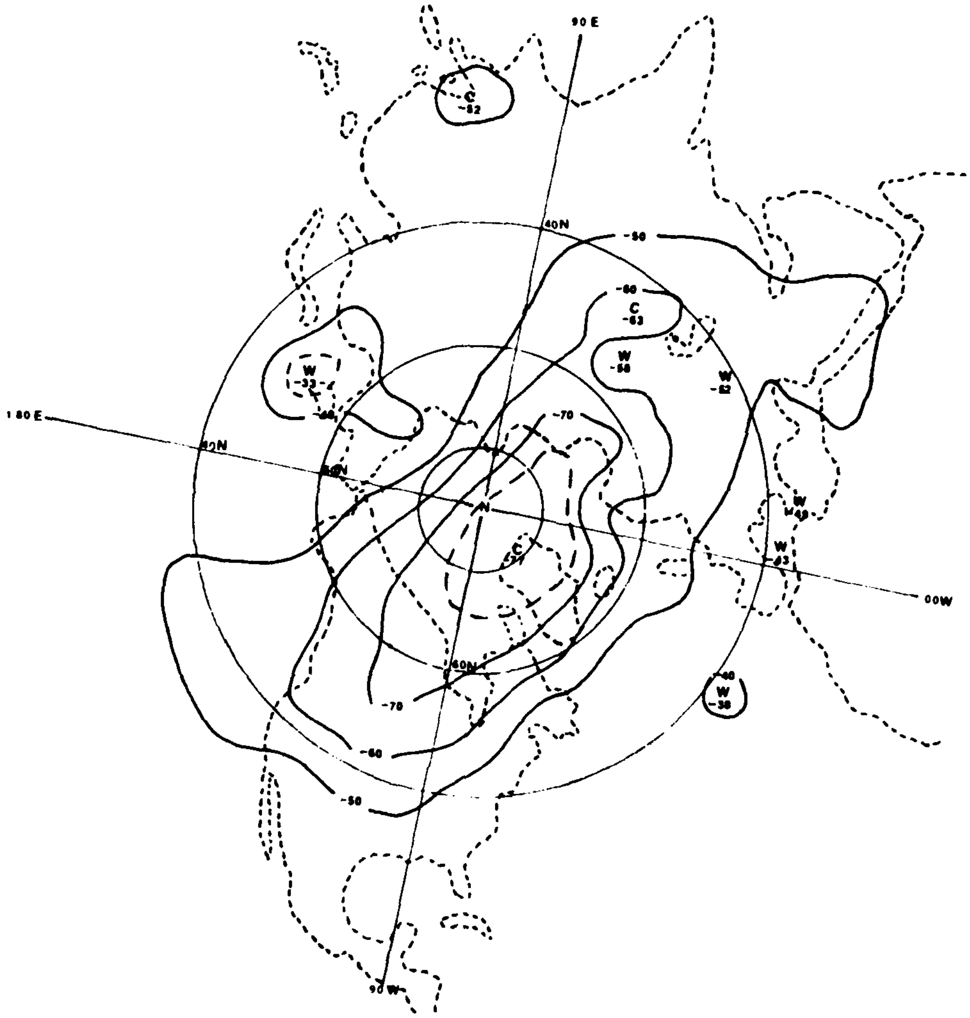


Fig. 6. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 10 Feb 1980. The contour interval is 10°C. Dashed lines represent intermediate contours.

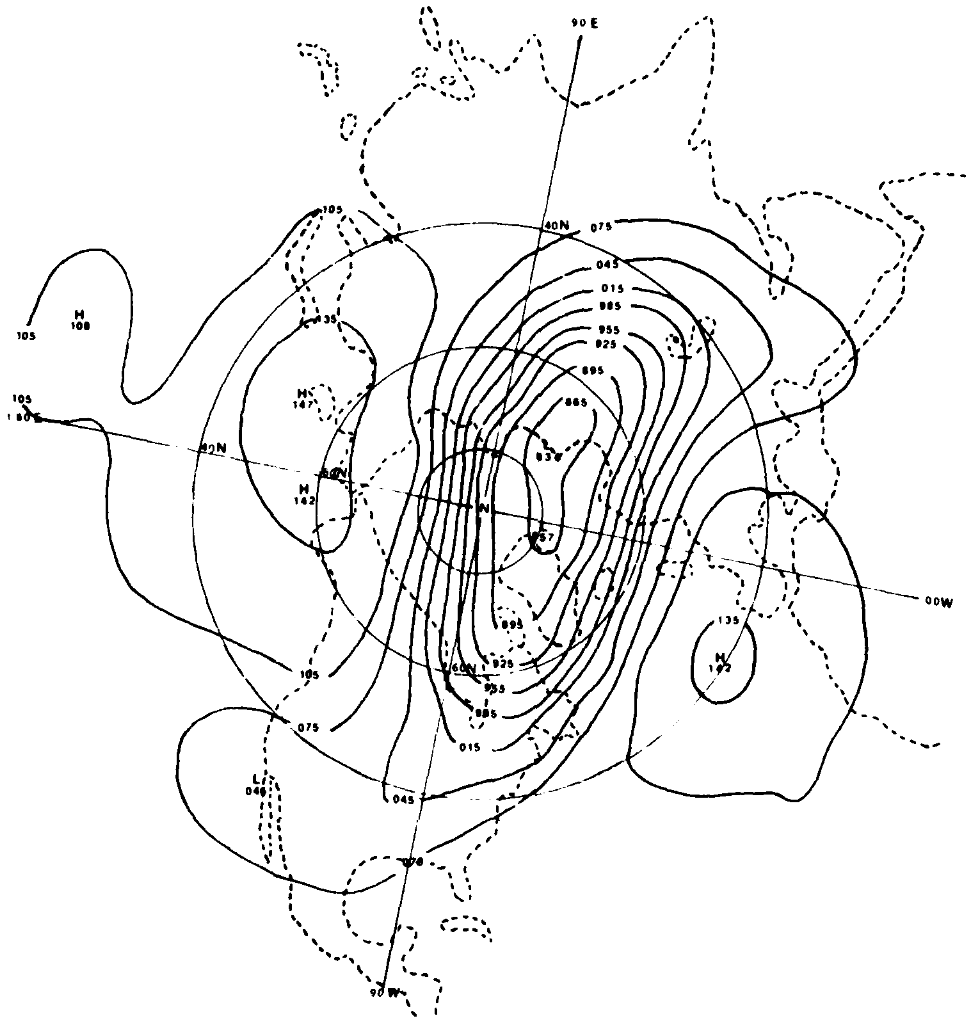


Fig. 7. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 18 Feb 1980. The contour interval is 300 m.

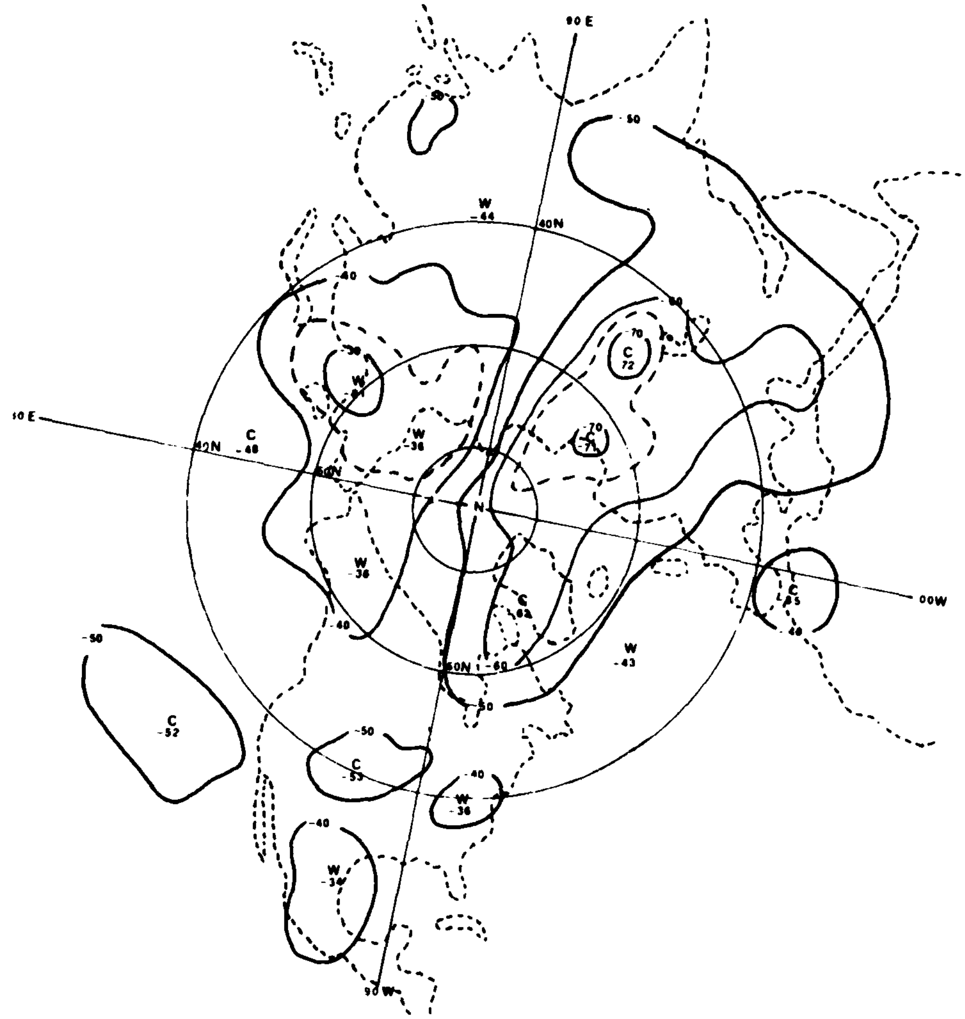


Fig. 8. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 18 Feb 1980. The contour interval is 10°C. Dashed lines represent intermediate contours.

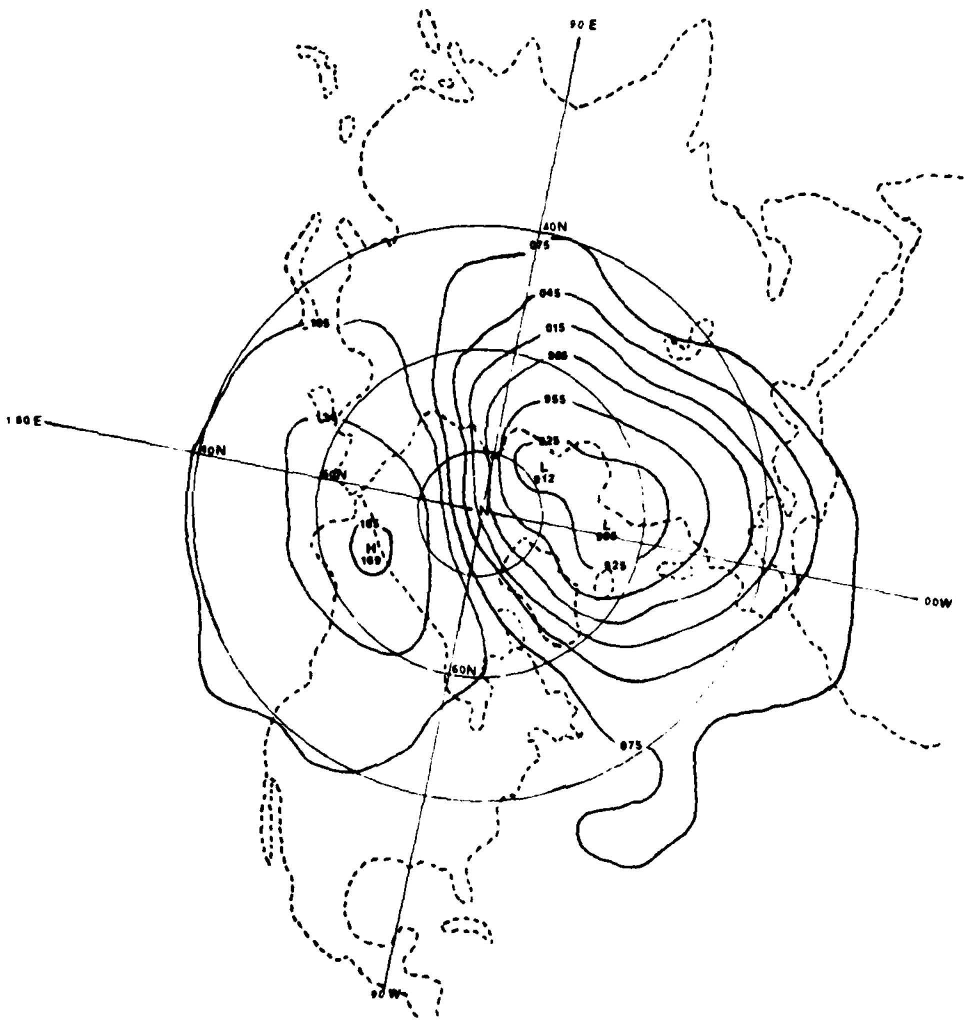


Fig. 9. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 28 Feb 1980. The contour interval is 300 m.

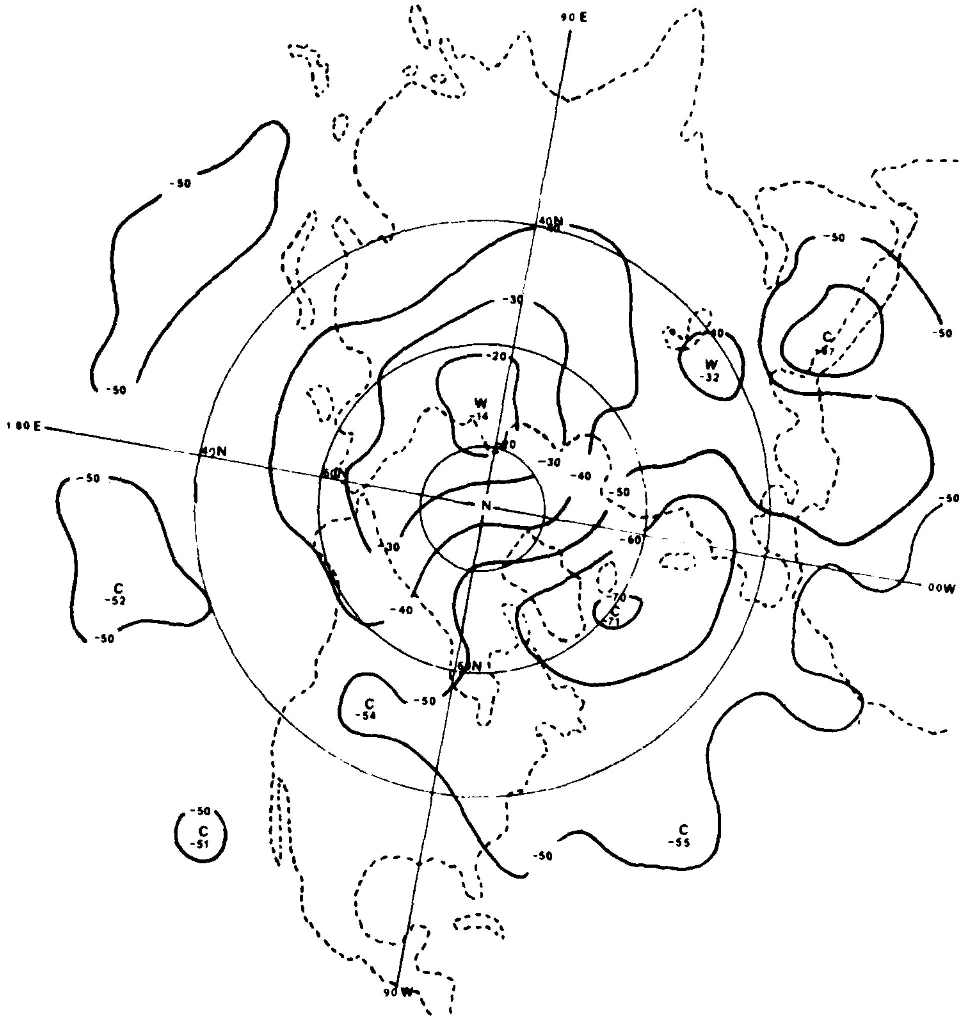


Fig. 10. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 28 Feb 1980. The contour interval is 10°C.

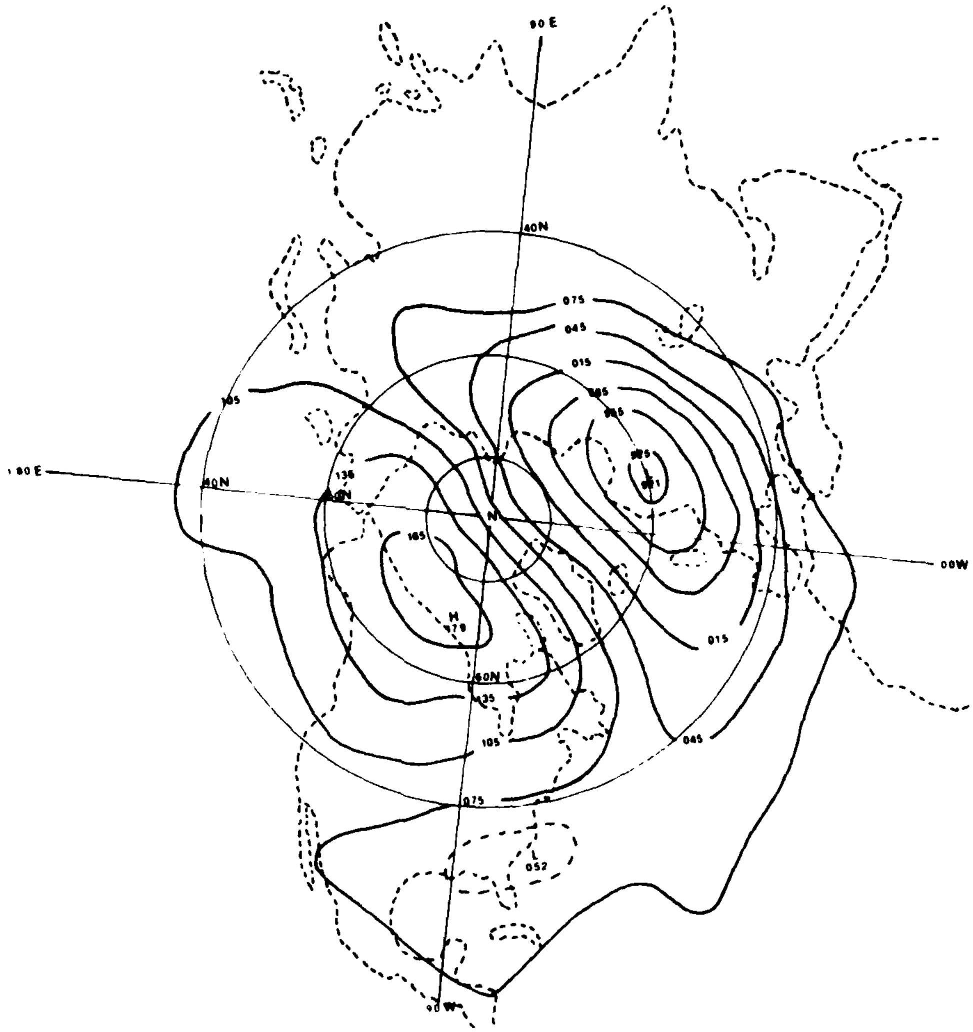


Fig. 11. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 2 Mar 1980. The contour interval is 300 m.

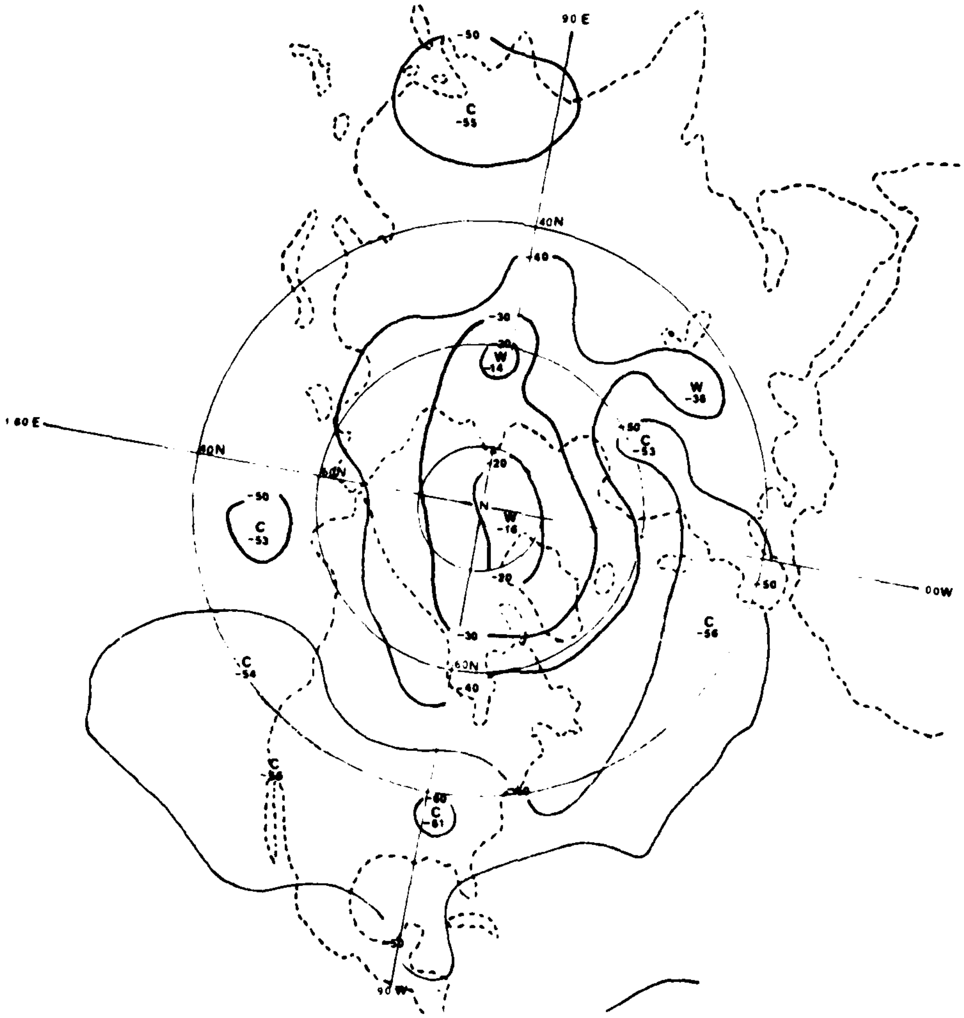


Fig. 12. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 2 Mar 1980. The contour interval is 300 m.

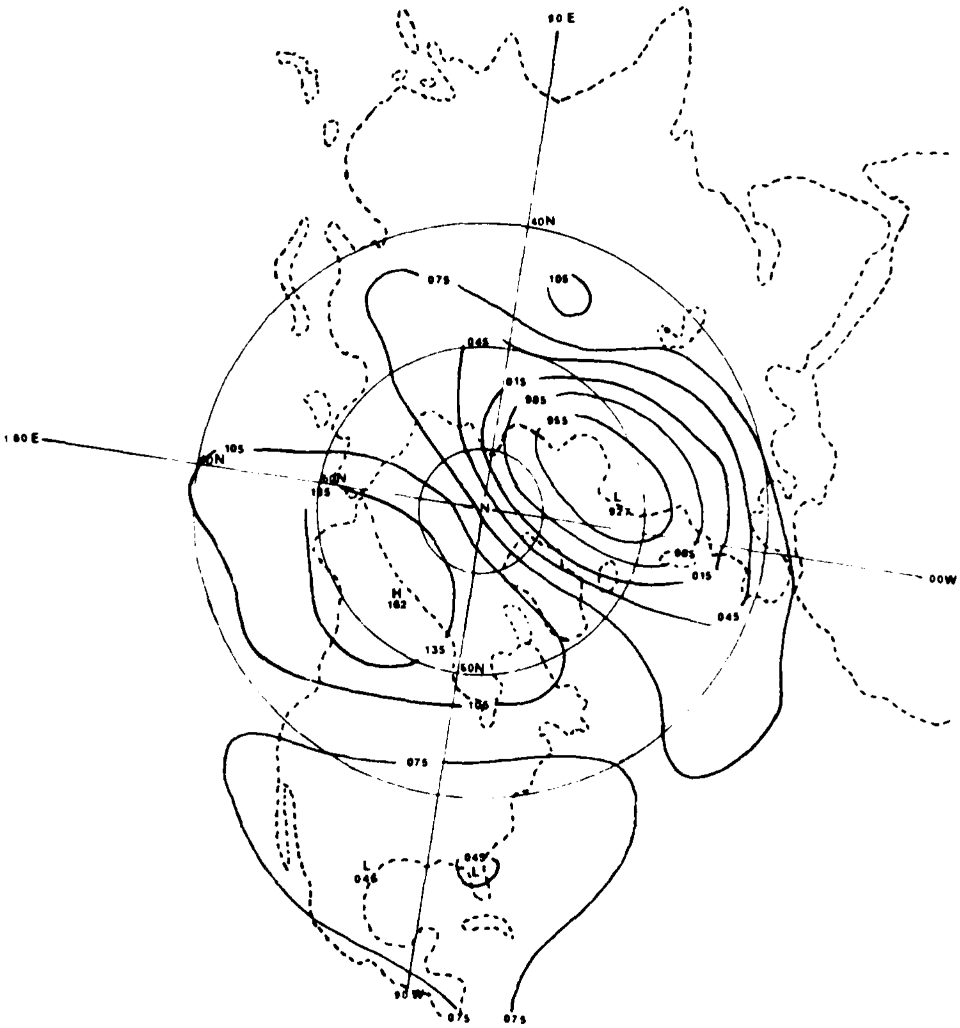


Fig. 13. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 4 Mar 1980. The contour interval is 300 m.

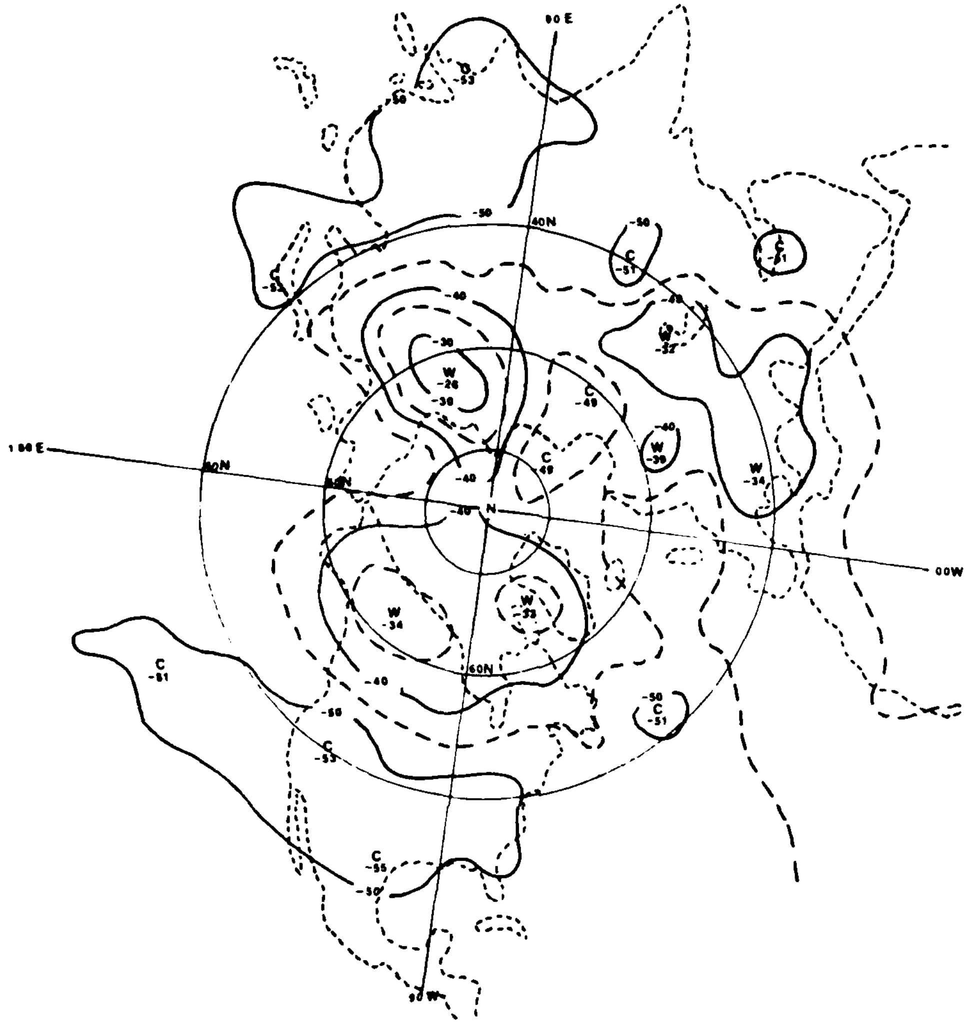


Fig. 14. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 4 Mar 1980. The contour interval is 10°C. Intermediate contours are dashed.

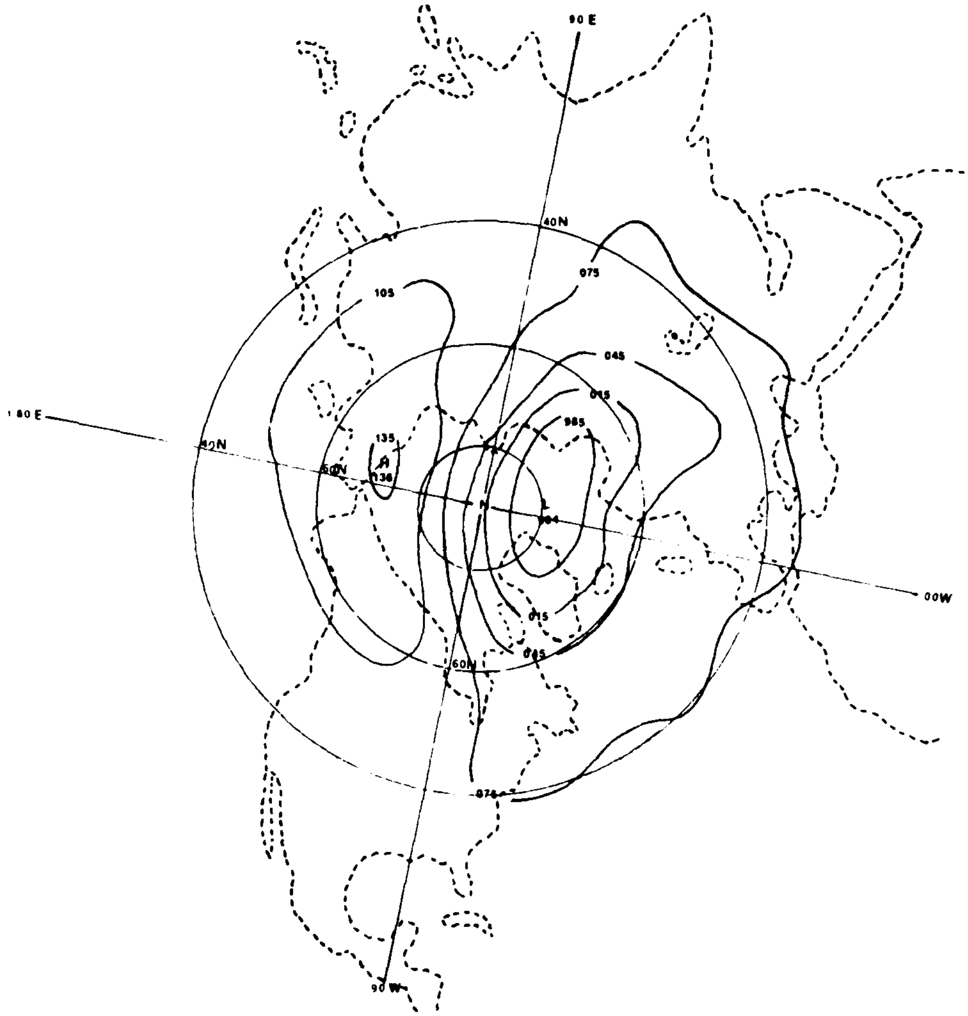


Fig. 15. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 12 Mar 1980. The contour interval is 300 m.

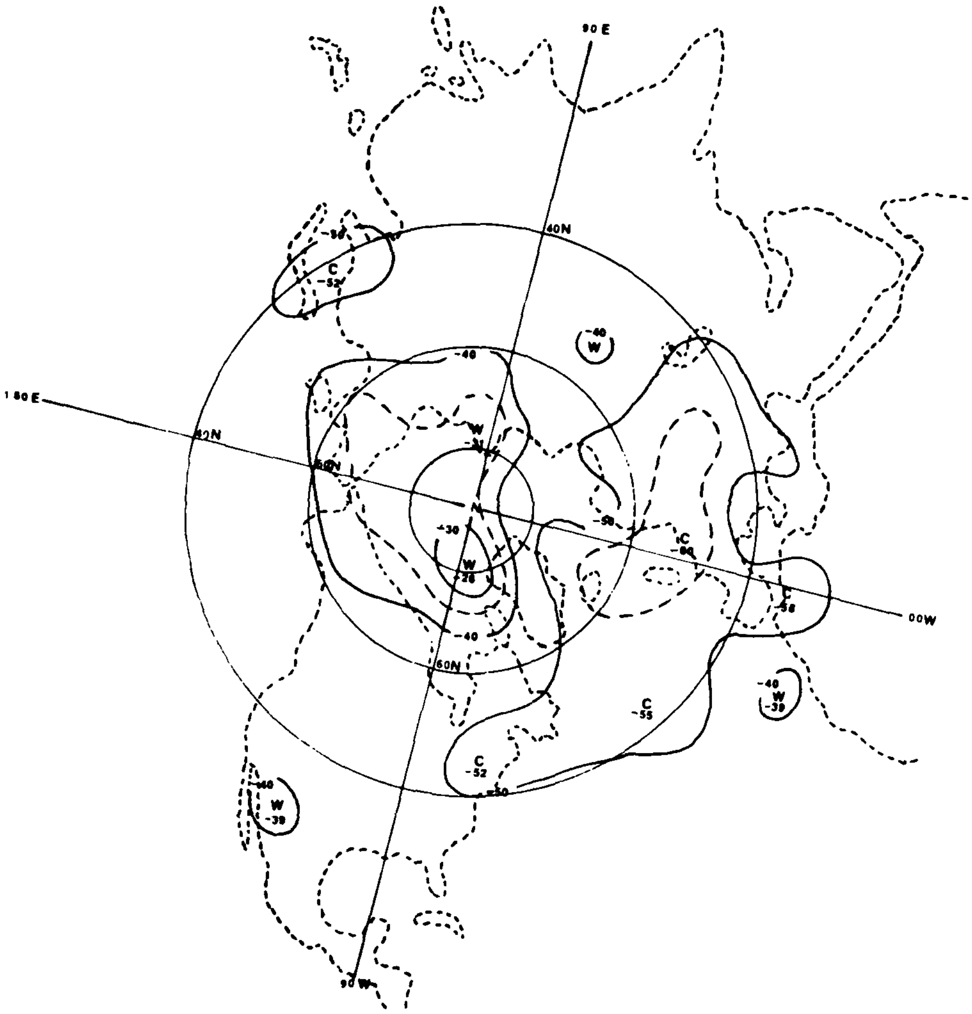


Fig. 16. Northern Hemispheric 10-mb temperature analysis for 12 GMT 12 Mar 1980. The contour interval is 10°C. Intermediate contours are dashed.

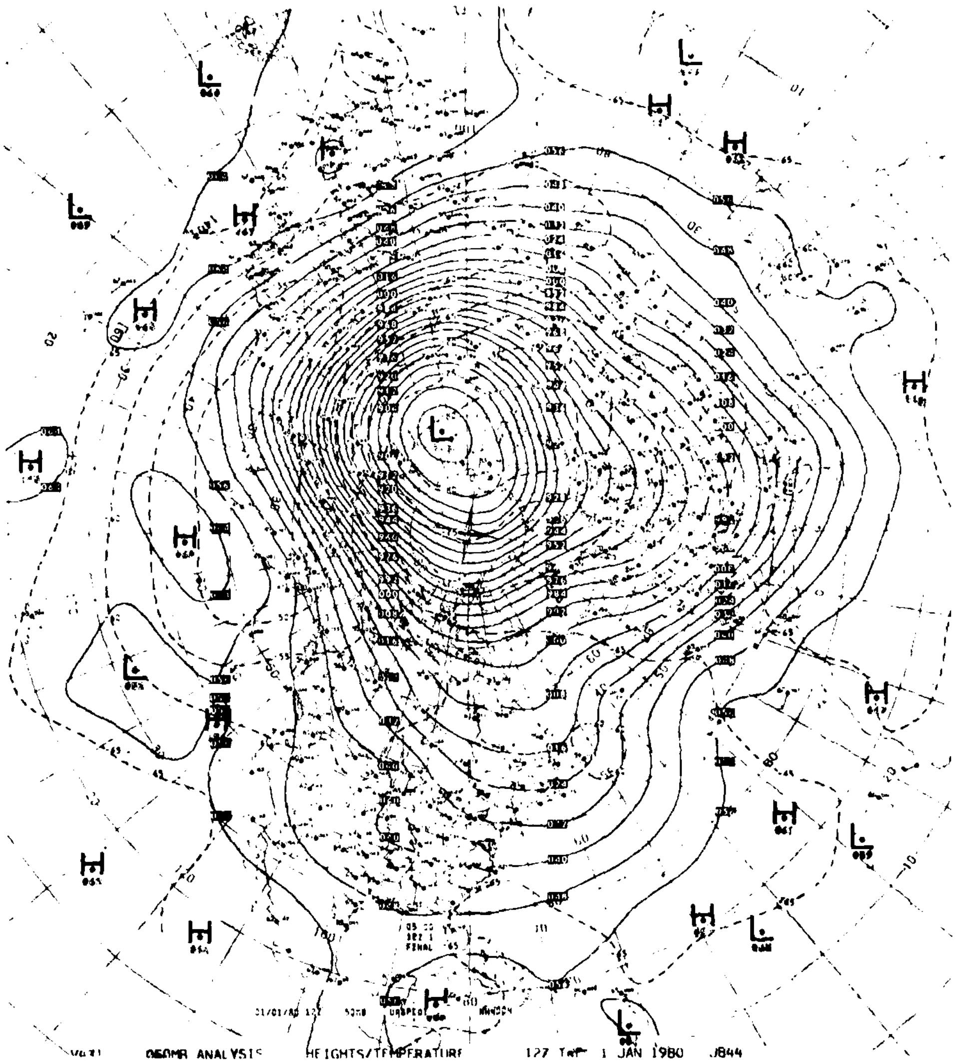


Fig. 17. NMC Northern Hemispheric 10-mb height and temperature analyses for 12 GMT 1 Jan 1980. The height contour interval is 80 m. The interval for isotherms (dashed lines) is 5°C.

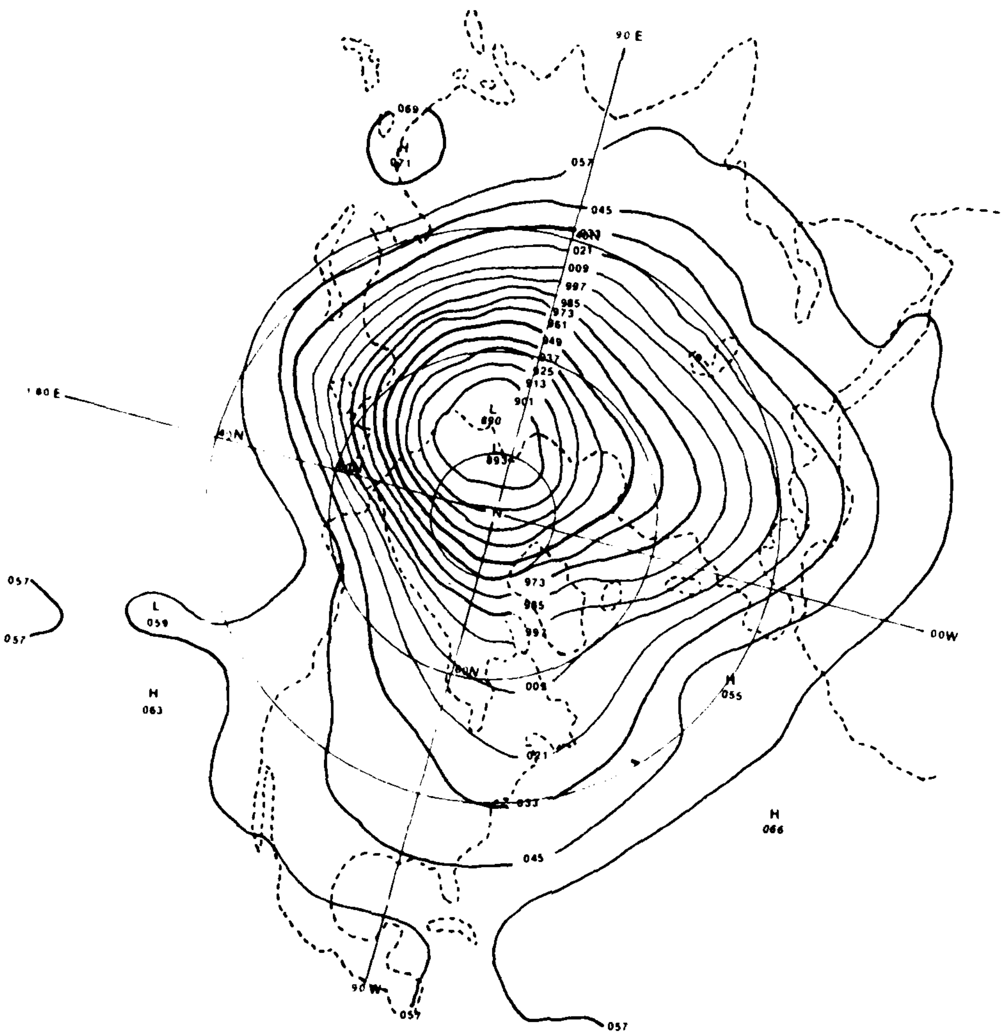


Fig. 18. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 1 Jan 1980. The contour interval is 120 m.

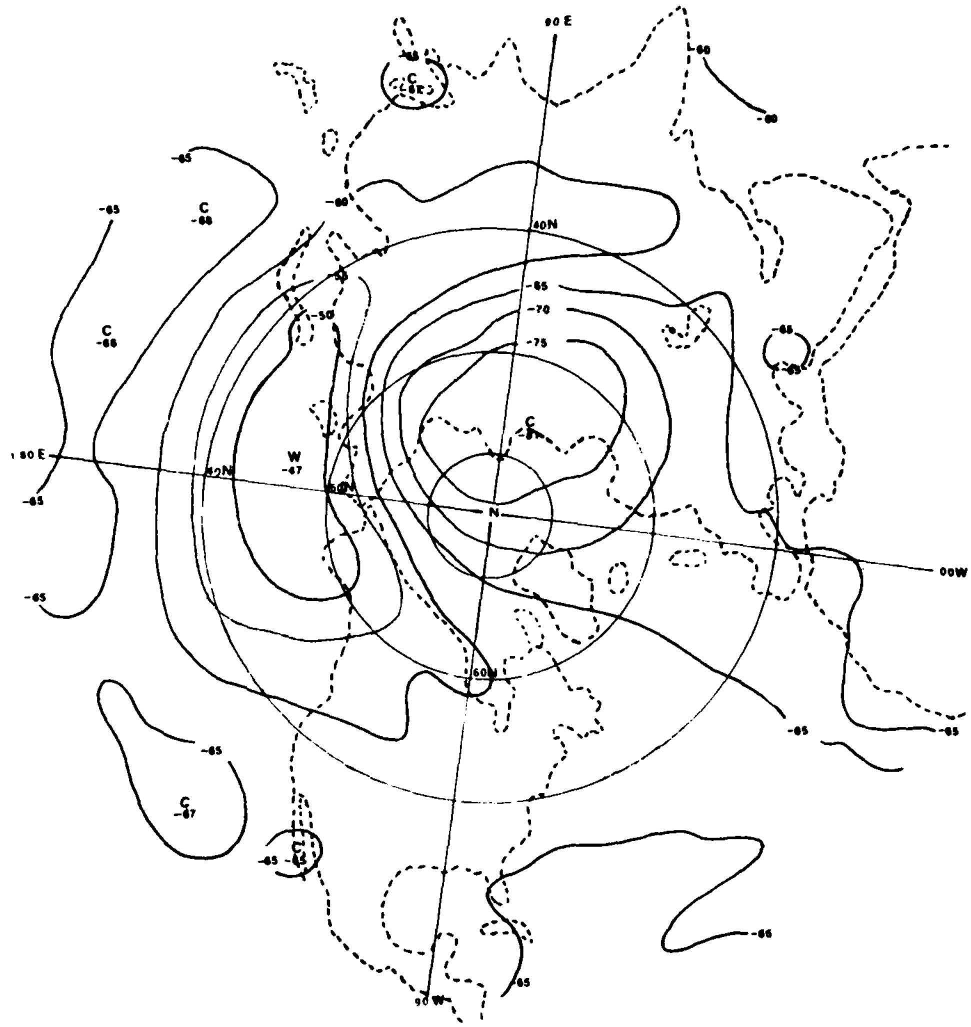


Fig. 19. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 1 Jan 1980. The contour interval is $5^{\circ}C$.

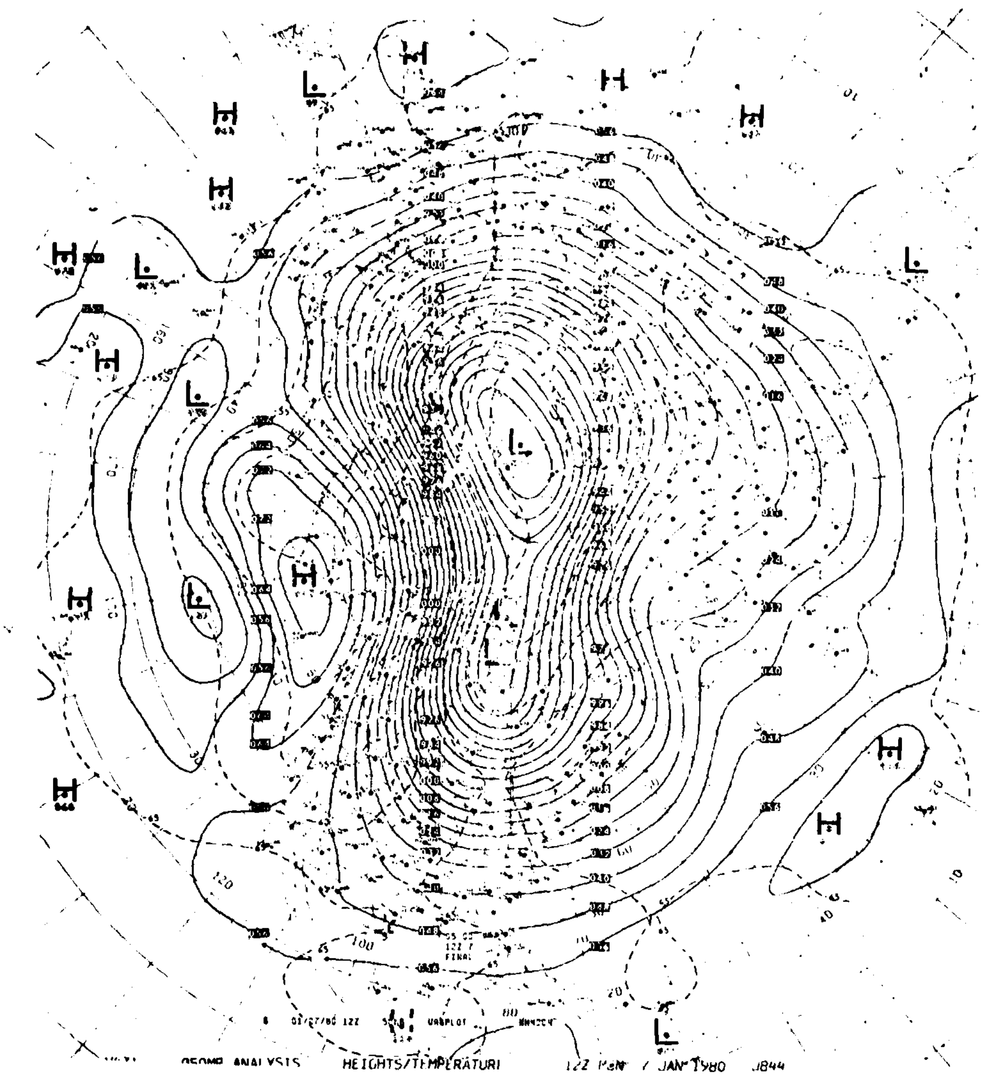


Fig. 20. NMC Northern Hemispheric 10-mb height and temperature analyses for 12 GMT 7 Jan 1980. The height contour interval is 80 m. The interval for isotherms (dashed lines) is 5°C.

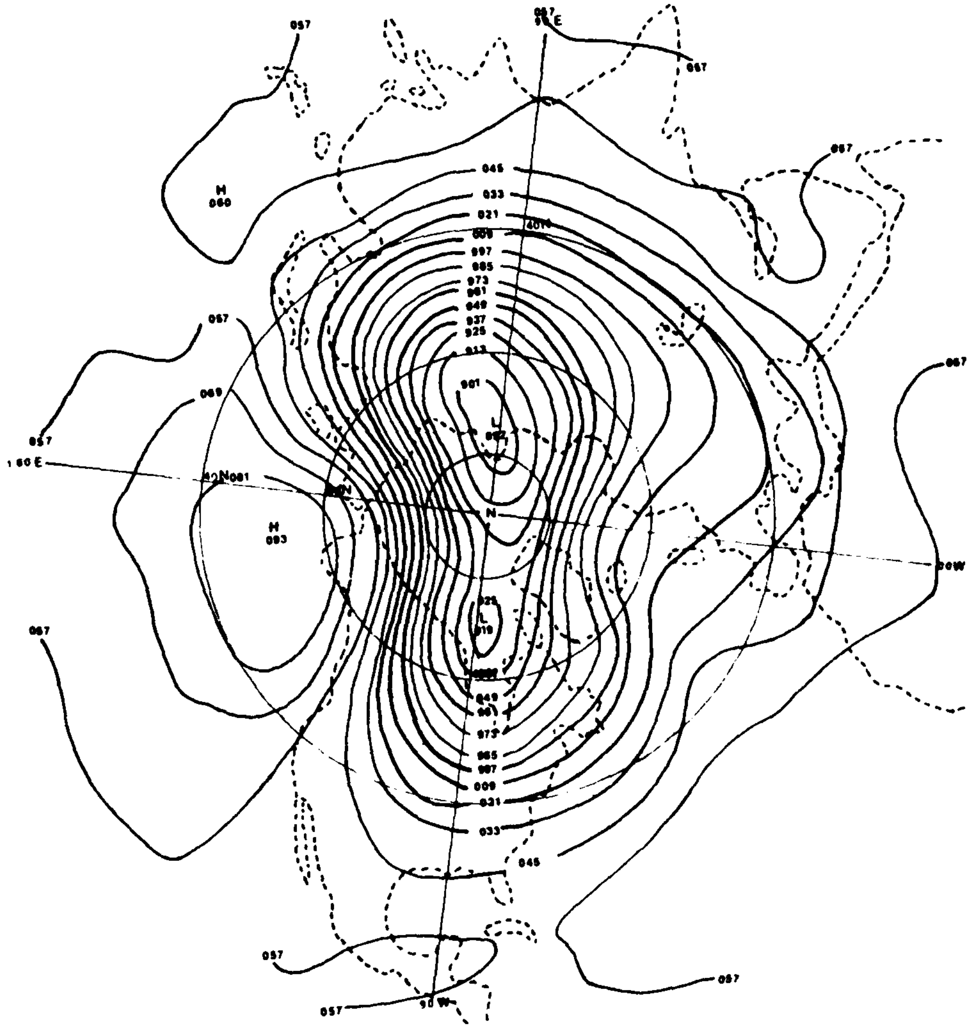


Fig. 21. AFGWC Northern Hemispheric 10-mb height analysis for 12 GMT 7 Jan 1980. The contour interval is 120 m.

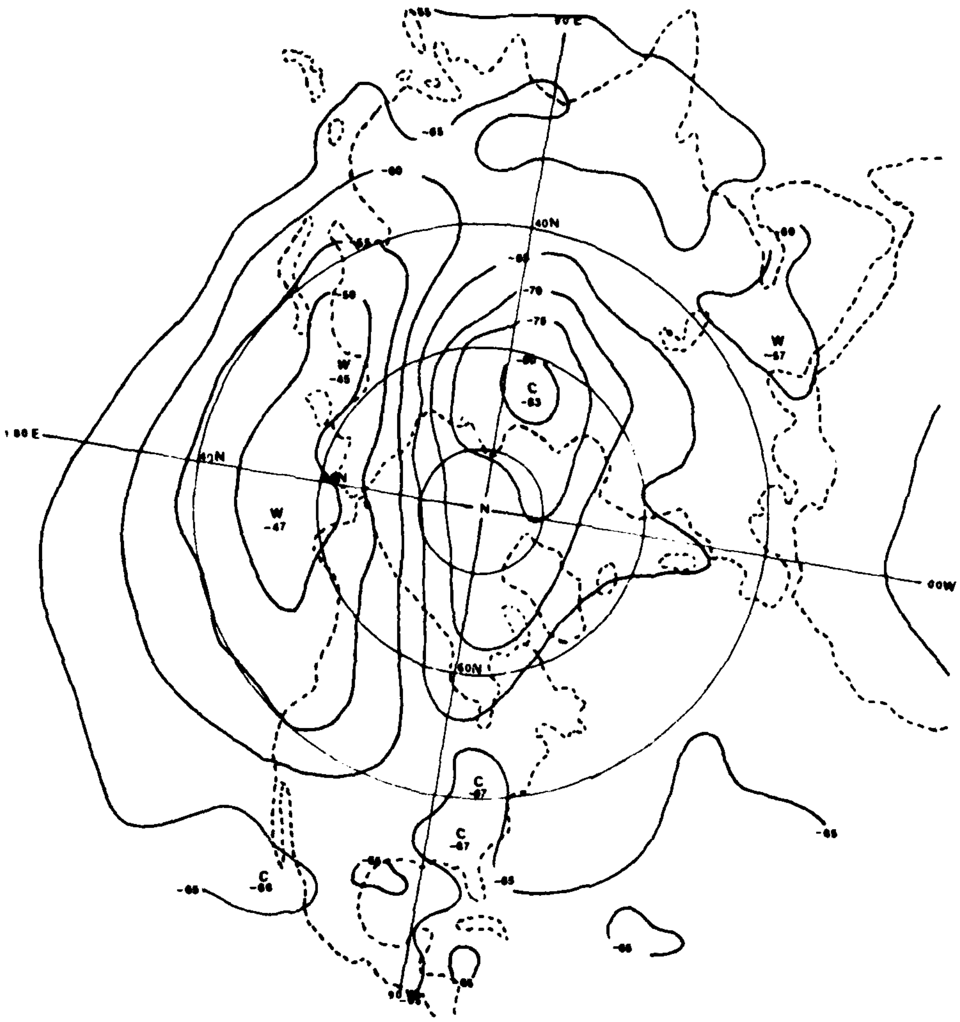


Fig. 22. AFGWC Northern Hemispheric 10-mb temperature analysis for 12 GMT 7 Jan 1980. The contour interval is 5°C.

7. SUMMARY AND CONCLUSIONS

This Technical Note documents the current use of satellite soundings in the AFGWC stratospheric analyses since 26 Dec 1979.

There were several reasons why the satellite observations were included in the AFGWC stratospheric analyses:

a. The nonmeteorological bullseye features could be eliminated.

b. The quality of the present DMSP and TOVS soundings in the stratosphere are comparable to RAOBs.

c. The amount of stratospheric data available to the analysis models more than doubles when satellite data are included.

d. NMC has had good results using the TOVS satellite soundings in the stratospheric analyses.

e. Coincident satellite observations are internally consistent whereas coincident RAOBs are not always consistent.

The old analysis procedure used a set of regression equations applied to the current 100-mb analysis to derive the 70-mb through 10-mb first-guess analysis. This first-guess field was then modified by the Cressman analysis procedure with existing RAOBs to form the final analysis.

The new AFGWC analysis procedure is similar to the one used operationally at NMC. The procedure uses the Cressman analysis technique to analyze satellite soundings spanning 12 h to derive the first-guess fields. Next the satellite first-guess analysis, is blended equally with the previous analysis (persistence) to form the final first-guess. The final first-guess fields are then modified by the Cressman analysis procedure with RAOBs and satellite observations within 3 h of the analysis time to form the final analysis.

Three case studies were presented. The first case demonstrated how the bullseye features could be eliminated by using satellite soundings and lowering the data throw criteria. The second case showed a Northern Hemispheric 10-mb sudden stratospheric warming during Feb and Mar 1980. The new AFGWC analysis procedure was able to analyze this sudden warming with no manual intervention. The final case compares the NMC and AFGWC Northern Hemispheric 50-mb analyses. The AFGWC analyses compare favorably with the NMC analyses. This is not surprising, because both use similar data types and analysis techniques.

The use of stratospheric satellite observations has improved the AFGWC global stratospheric analyses. The Tropical and Southern Hemispheric stratospheric analyses have been especially improved. Previously, a small amount of RAOBs was the primary data source in these regions. The analyses now have sufficient satellite data included to make them reliable for both operational mission planning and scientific study.

8. APPENDIX A - ABBREVIATIONS

AFGWC	Air Force Global Weather Central
DMSP	Defense Meteorological Satellite Program
GMT	Greenwich Mean Time
GTS	Global Telecommunications System
NESS	National Environmental Satellite Service
NMC	National Meteorological Center
NOAA	National Oceanographic and Atmospheric Administration
RAOB	Radiosonde or rawinsonde observation
SSH	Special Sensor H (infrared radiometer)
SSMT	Special Sensor Microwave Temperature (microwave radiometer)
TOVS	TIROS-N Operational Vertical Sounder
ULW	Ultra-long wave
USAFETAC	United States Air Force Environmental Technical Applications Center

9. APPENDIX B - REGRESSION EQUATION COEFFICIENTS

Eqs. (1) and (2) are the general forms of the stratospheric height and temperature regression equations. The coefficients A_n and B_n (n = 0, 1, 2) represent seasonal mean regression coefficients, which AFGWC obtained from NMC. Tables 2a, 2b, 2c, and 2d list the values for A_n and B_n at the 50-, 30-, and 10-mb levels for spring, summer, fall, and winter, respectively.

TABLE 3. Regression coefficients for Eqs. (1) and (2).

a. Spring (Mar - May)

	Regression Cooefficients					
Latitudinal Band	A_0	A_1	A_2	B_0	B_1	B_2
100-50 mb						
00-19	8790.3945	0.7610	0.9854	213.4120	-0.0150	0.0372
20-29	8404.6953	0.7850	0.9795	63.8390	-0.0070	0.0136
30-39	6869.7109	0.8910	1.2478	13.6540	-0.0030	0.0355
40-49	6072.8984	0.9400	1.2189	-14.2310	-0.0010	0.0429
50-59	5298.7500	0.9990	1.5172	-35.6930	0.0010	0.0622
60-69	4770.6953	1.0450	1.9263	-69.5460	0.0040	0.0903
80-90	4636.7344	1.0600	2.1590	-73.8120	0.0050	0.1160
50-30 mb						
00-19	1567.5010	1.1030	0.7604	-223.8260	0.0090	0.0253
20-29	1248.6741	1.1240	0.9354	-271.8130	0.0120	0.0473
30-39	2343.3291	1.0790	1.3120	-217.0290	0.0100	0.0728
40-49	3046.6440	1.0460	1.2970	-111.1540	0.0050	0.0814
50-59	3331.4670	1.0320	1.3044	-91.1100	0.0040	0.0828
60-69	3083.1360	1.0470	1.4267	-128.1450	0.0060	0.0915
70-90	3510.4861	1.0280	1.5079	-60.7900	0.0030	0.1040
30-10 mb						
00-29	8610.7187	1.0000	2.5283	-11.1430	0.0	0.0571
30-44	8688.1016	1.0000	2.6815	-6.3330	0.0	0.0667
45-59	8591.5703	1.0000	2.6815	-12.3330	0.0	0.0667
60-69	8666.6523	1.0000	2.9496	-7.6670	0.0	0.0833
70-90	8806.0898	1.0000	3.2178	1.0000	0.0	0.1000

b. Summer (Jun - Aug)

Latitudinal Band	A_0	A_1	A_2	B_0	B_1	B_2
	Regression Coefficients					
100-50 mb						
00-19	6767.2812	0.8880	1.0286	-11.2720	-0.0020	0.0232
20-29	7453.9023	0.8380	0.7881	-84.9840	0.0020	0.0105
30-39	5518.3555	0.9720	1.1590	-56.6980	0.0010	0.0247
40-49	5600.9727	0.9710	1.2272	-47.7800	0.0010	0.0373
50-59	4754.9219	1.0340	1.5306	-84.9070	0.0040	0.0578
60-69	4943.6992	1.0280	1.6823	-89.4180	0.0050	0.0795
70-90	5204.1328	1.0090	1.5324	-32.7879	0.0010	0.0576
50-30 mb						
00-19	3554.2410	1.0090	0.8329	-26.3740	0.0	0.0437
20-29	2537.2251	1.0550	0.7118	-139.5650	0.0050	0.0270
30-39	2588.3911	1.0601	1.0068	-127.2330	0.0050	0.0480
40-49	3097.9131	1.0370	1.0244	105.0020	0.0040	0.0511
50-59	3285.7520	1.0240	1.2770	-93.0550	0.0040	0.0762
60-69	1666.8291	1.0910	0.3316	-65.6970	0.0030	0.0902
70-90	3414.5190	1.0160	0.6728	-50.0410	0.0010	0.0283
30-10 mb						
00-29	8651.8281	1.0000	2.5549	-8.5880	0.0	0.0588
30-44	8769.8906	1.0000	2.8156	-1.2500	0.0	0.0750
45-59	8753.8008	1.0000	2.8156	-2.2500	0.0	0.0750
60-69	8824.8594	1.0000	2.9496	2.1670	0.0	0.0833
70-90	8918.7109	1.0000	3.2178	0.0000	0.0	0.1000

c. Fall (Sep - Nov)

Latitudinal Band	A_0	A_1	A_2	B_0	B_1	B_2
	Regression Coefficients					
100-50 mb						
00-19	7532.6836	0.8450	1.0955	-4.7890	-0.0020	0.0315
20-29	6622.1719	0.8950	0.9617	-28.8050	-0.0010	0.0205
30-39	5817.7266	0.9490	1.0671	-74.8930	0.0020	0.0251
40-49	4767.0937	1.0240	1.3404	-111.2200	0.0050	0.0461
50-59	5102.5430	1.0160	1.6946	-61.5650	0.0030	0.0772
60-69	4678.8984	1.0500	1.9325	-67.6820	0.0040	0.0971
70-90	4455.0859	1.0600	1.8378	-88.6060	0.0050	0.0901

50-30 mb						
00-19	1264.1631	1.1190	0.8162	-256.8940	0.0110	0.0402
20-29	2561.3311	1.0560	0.7987	-134.0850	0.0050	0.0375
30-39	2969.6299	1.0440	1.0759	-103.1010	0.0040	0.0565
40-49	2626.4380	1.0640	1.2209	-158.9490	0.0070	0.0704
50-59	3326.3440	1.0340	1.3883	-88.2170	0.0040	0.0898
60-69	3759.0491	1.0170	1.5533	-38.9390	0.0020	0.1067
70-90	4020.8521	1.0050	1.5946	27.9120	0.0010	0.1181
30-10 mb						
00-29	8412.3398	1.0000	2.1620	-23.3300	0.0	0.0333
30-44	8477.6797	1.0000	2.3530	-16.5000	0.0	0.0500
45-59	8579.6992	1.0000	2.6850	-12.3400	0.0	0.0670
60-69	8643.5781	1.0000	2.9638	-7.9500	0.0	0.0850
70-90	8769.6016	1.0000	3.2000	0.0	0.0	0.1000

d. Winter (Dec - Feb)

Latitudinal Band	Regression Coefficients					
	A_0	A_1	A_2	B_0	B_1	B_2
100-50 mb						
00-19	7745.8594	0.8190	0.9042	41.2010	-0.0050	0.0291
20-29	10768.5664	0.6190	0.5172	101.6670	-0.0100	0.0002
30-39	6699.0937	0.9010	1.2820	-16.8530	-0.0010	0.0421
40-49	4136.5000	1.0749	1.6621	-161.0970	0.0090	0.0722
50-59	5193.3477	1.0270	2.2087	-39.9000	0.0030	0.1182
60-69	5637.1602	1.0010	2.2699	25.8560	-0.0010	0.1230
70-90	5413.7344	1.0120	2.1970	5.6980	0.0	0.1169
50-30 mb						
00-19	2066.0171	1.0820	0.8713	-234.3790	0.0100	0.0422
20-29	1253.0291	1.1220	0.8897	-296.8250	0.0130	0.0418
30-39	3066.9170	1.0450	1.2832	-111.6250	0.0050	0.0785
40-49	3525.0569	1.0280	1.5081	-37.0620	0.0020	0.1060
50-59	4185.1484	0.9970	1.5814	24.6970	-0.0010	0.1104
60-69	4264.4922	0.9920	1.5360	67.6130	-0.0030	0.1142
70-90	5368.2578	0.9430	1.7587	177.5760	-0.0080	0.1326
30-10 mb						
00-29	8496.6484	1.0000	2.3333	-18.2330	0.0	0.0450
30-44	8480.0000	1.0000	2.4000	-19.2680	0.0	0.0492
45-59	8762.1836	1.0000	2.9496	1.6670	0.0	0.0633
60-69	8830.2227	1.0000	3.2178	2.5000	0.0	0.1000
70-90	8655.0000	1.0000	3.0000	-8.3910	0.0	0.0865

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